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Quaternary Studies in the Paradox Basin, Southeastern Utah

Technical Report

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of
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prepared for

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ABSTRACT

Since 1979, Quaternary and geomorphic studies in the Paradox Basin have focused on identification of Quaternary deposits and soils, and geomorphic processes that may affect the siting and integrity of a developed repository. Studies have included paleoclimatic assessments and evaluation of the Needles Fault zone, and an assessment of geologic age dating results and techniques.

Fossil pollen, snail shells, pack rat middens, and Holocene stratigraphic units have been examined as potential paleoclimatic indicators. Of these, the most definitive data have been an interpreted 13,000-year vegetation record found in the pack rat middens. This record defines the late Pleistocene-Holocene climatic transition at approximately 10,000 years ago, and indicates that temperature decreased and precipitation increased during the late Pleistocene relative to the present. In the Needles Fault zone, age dating results and geomorphic studies indicate that the northeastern grabens may be the youngest and that the system is at least 65,000 years old. Using this date and an assumed Colorado River incision rate, the maximum rate at which grabens have spread eastward from the river canyon can be estimated.

The most useful age dating techniques for the Paradox Basin are the accumulation of pedogenic carbonate in the soil profile, radiocarbon dating, thermoluminescence dating, amino acid diagenesis of mollusk shells, paleomagnetic analysis of early Pleistocene deposits, and topographic position of deposits and surfaces. Method applicability depends on the datable materials present, the estimated age of the sample or deposit, and potential contaminants that could affect analysis.

FOREWORD

The National Waste Terminal Storage (NWTS) program was established in 1976 by the U.S. Department of Energy's (DOE) predecessor, the Energy Research and Development Administration. In September 1983, this program became the Civilian Radioactive Waste Management (CRWM) Program. Its purpose is to develop technology and provide facilities for safe, environmentally acceptable, permanent disposal of high-level waste (HLW). HLW includes wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes from production of nuclear weapons, and solidified wastes from fuel reprocessing.

The information in this report pertains to the Paradox Basin geologic studies of the Salt Repository Project of the Office of Geologic Repositories in the CRWM Program.

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1.0 INTRODUCTION

Several siting criteria of the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) require that various aspects of Quaternary geology and geomorphology be studied to evaluate the suitability of a proposed repository site. These regulatory criteria require that a site setting has exhibited structural, tectonic, hydrogeologic, and geomorphic stability since the start of the Quaternary period. Additionally, the nature and rate of tectonic, structural, hydrogeologic, and geomorphic processes that have occurred since the start of the Quaternary period must be such that, when projected into the future, they should not affect, or should favorably affect, the ability of the geologic repository to isolate the waste.

Accordingly, the repository must remain below the depth of erosion and denudation during its lifetime and be sited in an area where no significant geologic event, such as local dissolution, faulting, igneous activity, folding, fracturing, uplift, or subsidence has occurred during Quaternary time. The potential effects of climatic changes on the geochemical, hydrologic, and geomorphic processes occurring in the vicinity of the site are also of particular interest.

The identification and correlation of Quaternary deposits and soils provide a means of addressing siting issues and evaluating the suitability of areas in the Paradox Basin for potential repository sites. These tasks are most easily and reliably accomplished when the age of the deposits or soils of interest can be ascertained. Dates provide a means of correlation and can be used to establish the rates at which geologic processes are occurring, thereby addressing many of the technical criteria outlined in 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories; Technical Criteria. Interpretations derived from the dated deposits can also be used to reconstruct conditions, such as climatic controls, that would have affected the deposits or soils at the time of their formation. These climatic conditions and their effect on geomorphic processes can then be projected into the future to assess potential effects of future climatic variability, another regulatory issue. Therefore, the dating of Quaternary deposits has comprised a significant aspect of the Geomorphology/Quaternary History discipline of the Paradox Basin studies.

1.1 HISTORY OF QUATERNARY STUDIES

Quaternary studies have been a technical discipline of Paradox Basin studies since regional evaluations were begun by Woodward-Clyde Consultants (WCC) in 1979. In the initial geologic overview of the Paradox Basin study region, the types and occurrence of Quaternary deposits were described, and an estimate of the long-term rates of incision and scarp retreat was given. This work (WCC, 1983) was based on a review of available literature.

Field studies began in 1979 and continued intermittently through September 1982. The aerial and ground surveys of summer 1979 provided an overview of the area, and focused on identifying areas where additional work was feasible and would be most effective for obtaining data. Efforts were concentrated in successive years on these specific data locations. Data collected prior to January 1982 were reported in the Geologic Characterization Report for the study areas (WCC, 1982a) within the Paradox Basin study region. Overviews of geomorphic processes that are and have been occurring in the Paradox Basin, erosion rates, paleoclimatic variability, and Quaternary deposits and soils were discussed in this report for the entire region, and for the Gibson Dome, Elk Ridge, Lisbon Valley, and Salt Valley study areas (WCC, 1982a). These reports included dating and pedologic analyses of samples collected during the previous field seasons (primarily 1980 and 1981). However, not all the data had been received from the analytical laboratories when the 1982 reports were compiled; these data are reported in this document.

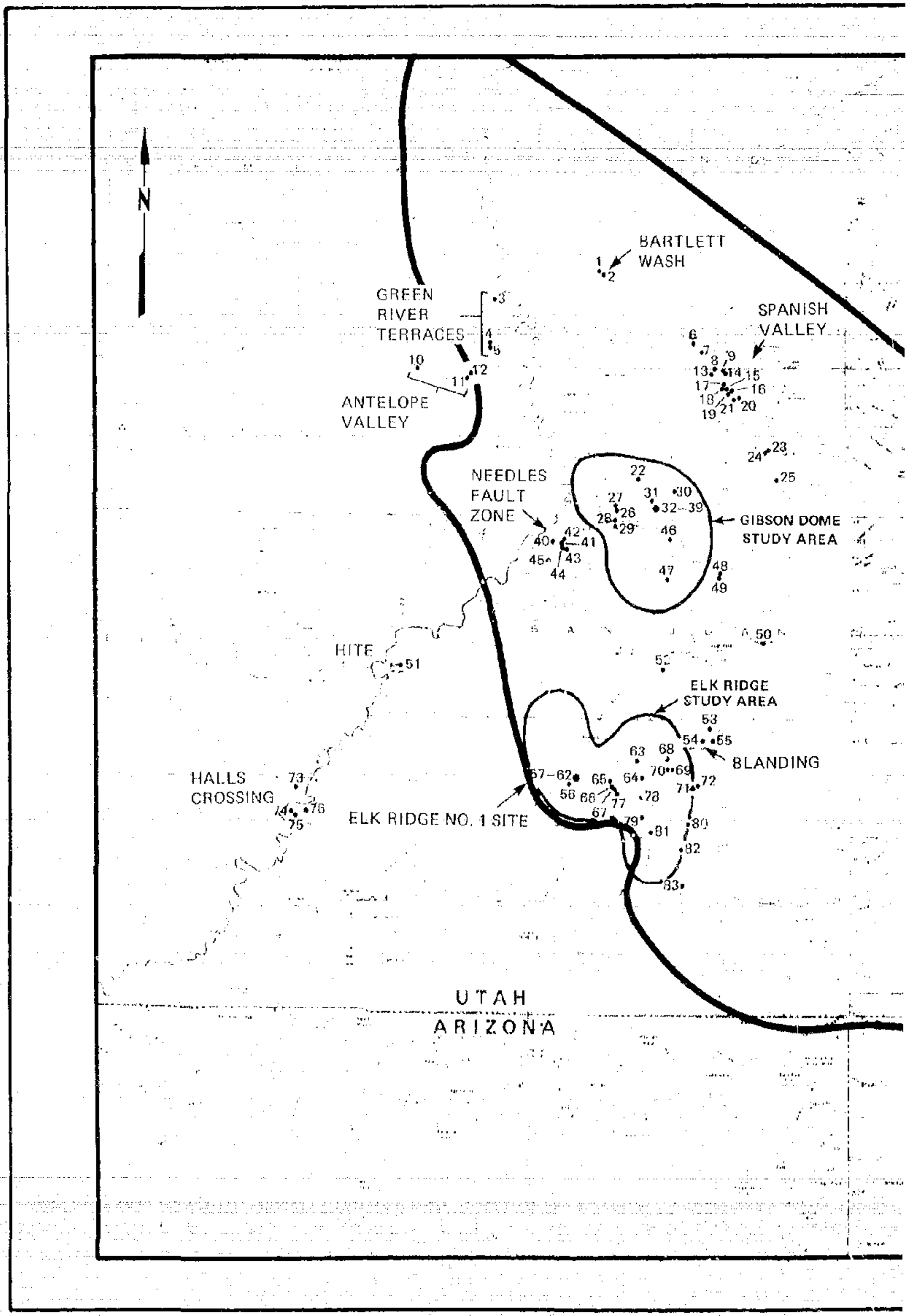
The brief (3 weeks) 1982 field effort was in support of future characterization of the Davis and Lavender Canyon sites. It focused on collecting geologic and macrofossil data in order to reconstruct paleoclimatic conditions, and to make a preliminary assessment of the deformational history of the Needles Fault zone of Canyonlands National Park. The character and variation in Holocene deposits in the Salt Creek drainage, which lies along the eastern border of the park, were examined to identify sedimentologic changes that might be attributed to climatic change. A subcontractor collected pack rat middens to assess the feasibility of reconstructing paleoclimates from plant macrofossils, and several geologic samples were collected to date Holocene deposits in the Needles Fault zone and along Salt Creek. Laboratory analyses of the 1982 samples were completed in December 1983. The pack rat data were subsequently published as a separate report (Betancourt and Biggar, 1985); the results of the Canyonlands studies are reported in Chapters 2 and 3.

1.2 PURPOSE AND ORGANIZATION OF REPORT

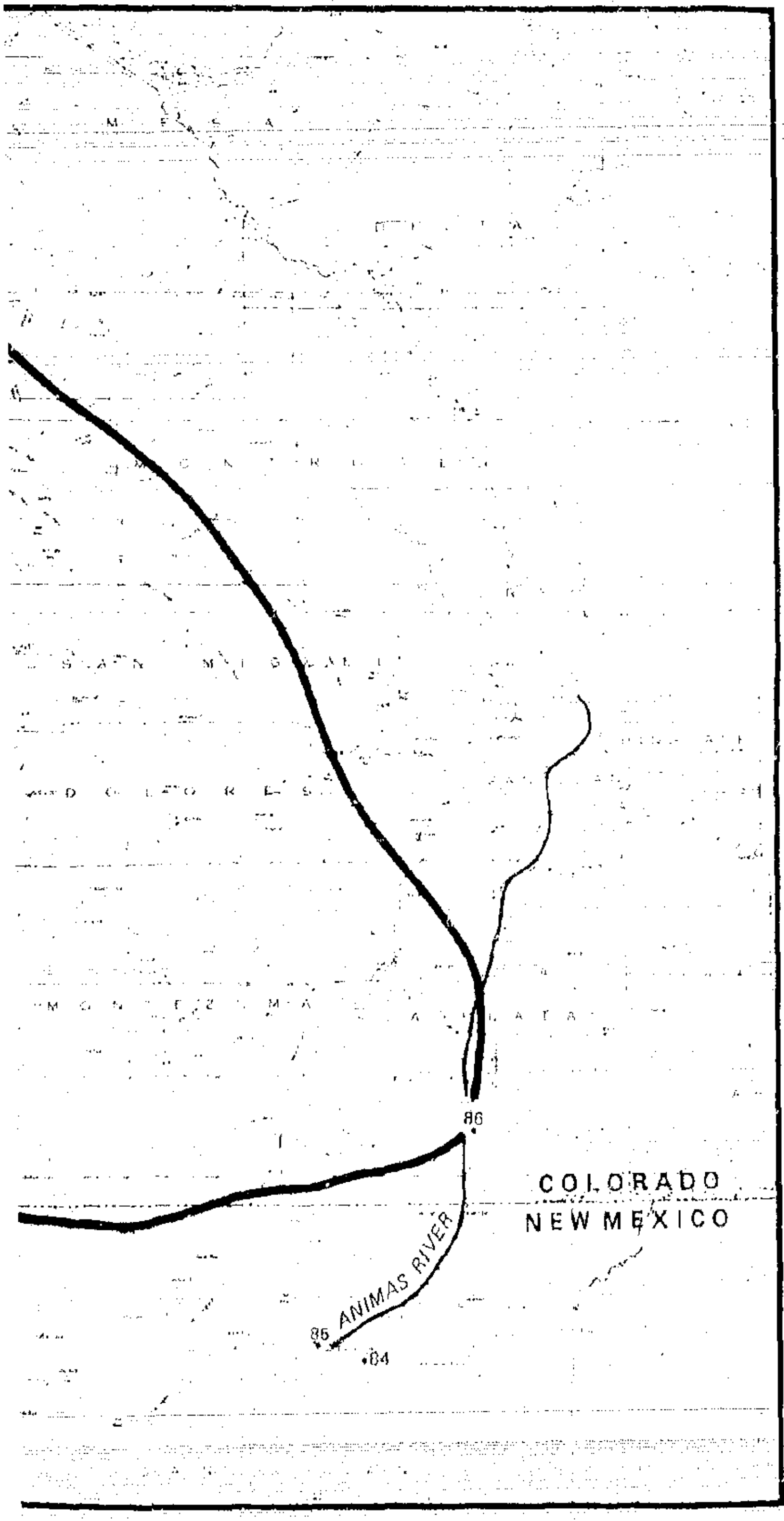
The purpose of this report is twofold. First, it presents the results of studies completed since the compilation of the Geologic Characterization Report (WCC, 1982a). Accordingly, Chapter 2 contains the results of late Pleistocene/Holocene paleoclimatic studies conducted to date; data gathered on the Quaternary history of the Needles Fault zone are discussed in Chapter 3.

The second objective of the report is to provide a compilation and an assessment of the geologic dates that have been derived from Quaternary deposits and soils sampled during the course of the project. Chapter 4 presents the results of determinations and estimates that have been made by laboratory analyses of samples collected since the project began. Most of these dates have been given in previous reports in the context of describing and correlating Quaternary deposits and soils. However, they have not been evaluated as an entity in terms of the reliability and applicability of specific techniques, nor has the comparison of results obtained from multiple techniques been compared for single locations. Chapter 4 is a compilation and evaluation of all the dating techniques that have been used on this project. In addition to the application of this information to the geologic characterization of the site, the data are also of interest to those in the scientific community who are working in similar geologic and physical environments.

Localities referred to throughout the text are shown on Figure 1-1; age data relating to those localities are listed in Table 1-1. For convenience, many of the data given in Table 1-1 are organized into smaller tables in Chapter 4, where the data are discussed and evaluated.


N
BARTLETT WASH
GREEN RIVER TERRACES
ANTELOPE VALLEY
SPANISH VALLEY
NEEDLES FAULT ZONE
GIBSON DOME STUDY AREA
HITE
ELK RIDGE STUDY AREA
BLANDING
HALLS CROSSING
ELK RIDGE NO. 1 SITE
UTAH
ARIZONA

LOG: 1600



LEGEND:

BOUNDARY OF PARADOX BASIN

• 68 LOCALITY NUMBER (SEE TABLE 1-1)

0 10 20 30 mi

0 10 20 30 40 km

MAP OF LOCALITIES HAVING GEOLOGIC AGE DATA

Quaternary Topical Report

Project No. 17000
Woodward-Clyde Consultants

Figure 1–1

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
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Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	C[f]	Pedogenesis: $CaCO_3$[g]	Pedogenesis: Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: x	+	#	Comments
1	T24S, R17E, Sec.15-1	Fine-grained alluvium	Early Holocene-Late Pleistocene		x	(x)							<730				Wash north of Bartlett Wash
2	T24S, R17E, Sec.23-2	Fine-grained alluvium:	Early Holocene-Late Pleistocene	x	x	(x)							<730				Bartlett Wash
		• snails (10 m)										ca 11-15					
		• tusk (14 m)								[(n) 12.98±0.37 >35]	45±1 to 48±4						
3	T25S, R16E, Sec.11-1	Alluvial gravel	Early Pleistocene	ca 1100	x	x	400-650		"Unsuitable"					x			Green River terrace
4	T26S, R16E, Sec.14-1	Alluvial sand and pebble gravel	Early Pleistocene	ca 1350	x	x			["too inhomogeneous": 134±19.3]								Red Knoll
5	T26S, R16E, Sec.14-2	Alluvial gravel and sand	Early Pleistocene	ca 1350	x	x							>730(?)				Red Knoll
6	T26S, R22E, Sec.7-1	(a) Eolian deposit or fine-grained alluvium, over	Late Pleistocene		x	x									x		Spanish Valley, Moab gravel pit
		(b) Alluvial gravel	Late Pleistocene	ca 75-100	x	x	245-405				5±1 prob 72±6 max		<730		x		
7	T26S, R22E, Sec.27-1	Eolian deposit and/or fine-grained alluvium:	Late Holocene	x	x	(x)	7-12						<730		x		Spanish Valley, Gold Basin Formation
		• silt (1.2 m)							"too young"								
		• charcoal (1.9 m)								1.28±0.055							
		• silt (2.0 m)							7.48±0.61								
8	T26S, R22E, Sec.35-2	Fine-grained alluvium	Modern	x	x	(x)								x			Spanish Valley, modern floodplain

			Estimated Age, Basis				Ages or Age Interpretation Based on Laboratory Analyses[b]							Weathering[c]			
	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)					Pedogenesis										
Locality[a]			Age	Topo[d]	T[e]	C[f]	$CaCO_3$[g]	Clay[h]	Th[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	X	H	W	Comments
9	T26S, R23E, Sec.32-1	Alluvial gravel	Early Pleistocene	ca 1100	x	x			263.17±45.22				>730				Spanish Valley; Johnson's-Up-On-Top; lower member, Harpole Mesa Fm.
10	T27S, R14E, Sec.2-1	Eolian deposit	Modern	x	x	(x)											Antelope Valley, 7.9% $CaCO_3$ in <200μ fraction
11	T27S, R16E, Sec.7-1	Eolian deposit	Modern	x	x	(x)											Antelope Valley, 6.0% $CaCO_3$ in <200μ fraction
12	T27S, R16E, Sec.5-1	Eolian deposit, over fine-grained alluvium	Early to Mid-Pleistocene	ca 1550	x	x	>730	x					Questionable	x			Antelope Valley
13	T27S, R22E, Sec.2-1	(a) Fine-grained alluvium, over	Early Holocene to Late Pleistocene		x	(x)	x										Spanish Valley, permeability pit
		(b) Alluvial gravel:	Late Pleistocene		x	x	x										
		• 4Cca2 soil (1.4-1.5 m)							17.7±1.51			x					
		• 4k2mb3 soil (1.8 m)							78.2±4.8			x					
		• 5B2tcab4 soil (3.6-3.8 m)							114.32±9.42			x					
14	T27S, R23E, Sec.5-2	(a) Eolian deposit, over	Late Pleistocene		x	x		x						x			Spanish Valley; Johnson's-Up-On-Top; lower member, Harpole Mesa Fm.
		(b) Alluvial gravel	Early Pleistocene	ca 1100	x	x	>730	x	157.78±12.43			x	see #9	x		x	
15	T27S, R23E, Sec.16-1	(a) Eolian deposit, over	Late Pleistocene		x	x		x						x			Spanish Valley; upper member, Placer Creek Fm.
		(b) Alluvial gravel	Late Pleistocene	ca 150	x	x	150-245	x	238.31±18.52			x		x		x	

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
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Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age Basis: Age	Topo[d]	T[e]	C[f]	Pedogenesis: $CaCO_3$[g]	Pedogenesis: Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
16	T27S, R23E, Sec.17-1	(a) Eolian deposit, over	Late Pleistocene		x	x											Spanish Valley, upper member, Beaver Basin Fm.
		(b) Alluvial gravel	Late Pleistocene	ca 40	x	x	35-60	x	42.4±2.77			x		x		x	
17	T27S, R23E, Sec.18-1	(a) Eolian deposit, over	Late Pleistocene		x	x											Spanish Valley; lower member, Placer Creek Fm.
		(b) Alluvial gravel	Late Pleistocene	ca 100	x	x	145-240	x	108±8.8			x		x		x	
18	T27S, R23E, Sec.18-2	(a) Eolian deposit, over	Late Pleistocene		x	x		x	11.9±0.76					x			Spanish Valley; lower member, Beaver Basin Fm.
		(b) Alluvial gravel	Late Pleistocene	ca 50	x	x	30-45	x	9.29±0.7			x		x		x	
19	T27S, R23E, Sec.20-1	(a) Eolian deposit, over	Late Pleistocene		x	x											Spanish Valley; lower member, Placer Creek Fm.
		(b) Alluvial gravel	Late Pleistocene	ca 225	x	x	150-255	x	[111±12 / 127±16.4]			x		x		x	
20	T27S, R23E, Sec.22-1	(a) Eolian deposit; over	Late Pleistocene		x	x			22.5±2								Spanish Valley; middle member, Harpole Mesa Fm.; Amasas Back, 2nd pit
		(b) Alluvial gravel:	Mid-Pleistocene	ca 750	x	x	115-195	x						x			
		• 2K2mb soil (0.4 m)							[67.6±5.3 / >315]			x					
		• 5Coxb soil (0.4 m)							102.75±13.4			x					
21	T27S, R23E, Sec.28-1	(a) Eolian deposit; over	Late Pleistocene		x	x			2.36±0.22								Spanish Valley; middle member, Harpole Fm.; Amasas Back, 1st pit
		(b) Alluvial gravel:	Mid-Pleistocene	ca 750	x	x	165-275	x						x		x	
		• 2K2b soil (0.4-0.5 m)							[319±37 / 124.21±10.37]			x					
		• 3bicsb2 soil (2.1 m)							>200			x					

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 4 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (Depth)	Estimated Age, Basis: Age	Topo[d]	(e)	(f)	Ages or Age Interpretation Based on Laboratory Analyses[b]: Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[n]: X	H	W	Comments
22	T29S, R20E, Sec.35-1	Eolian deposit	Late Pleistocene	25-50	x				[37.4±7 76.8±10.1]								Alluvial fan near Lockhart Basin
23	T29S, R24E, Sec.5-1	(a,b) Eolian deposit and fine-grained alluvium, over	(a) Holocene		x	(x)									x		Lackey Creek, La Sal
			(b) Late Pleistocene		x								<730		x		
		(c) Alluvial gravel	(c) Late Pleistocene		x								<730		x		
24	T29S, R24E, Sec.5-2	Sand lens in gravel alluvium	Late Pleistocene		x								<730				Lackey Creek, La Sal
25	T29S, R24E, Sec.5A-1	Eolian deposit	Late Pleistocene		x	x							<730				Lisbon Valley
26	T30S, R20E, Sec.17-1	Fine-grained alluvium:	Holocene	x	x	(x)											Salt Creek, north of road
		(a) rhythmic beds, over								0.31±0.06							
		(b) sand:								102% modern							
		• upper								["no carbon"							
		• lower								"no carbon" 1.735±0.2]							
27	T30S, R20E, Sec.17-2	Fine-grained alluvium:	Holocene	x	x	(x)											Salt Creek, north of road.
		(a) rhythmic beds								3.360±0.19							
		(b) transitional beds								2.08±0.2 2.92±0.22 2.53±0.21 1.46±0.25 2.5±0.21							
		(c) sand								[1.71±0.26 1.79±0.37]							
28	T30S, R20E, Sec.29-1	Fine-grained alluvium: rhythmic beds	Holocene	x	x	(x)				4.51±0.6							Salt Creek, south of road, at stream crossing

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
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			Estimated Age, Basis				Ages or Age Interpretation Based on Laboratory Analyses[b]							Weathering[c]			
	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)					Pedogenesis										
Locality[a]			Age	Topo[d]	[illegible][e]	[illegible][f]	$CaCO_3$[g]	Clay[h]	TL[i]	14C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	X	H	W	Comments
29	T30S, R20E, Sec.32-2	Fine-grained alluvium: (a) Rhythmic beds:	Holocene	x	x	(x)											Salt Creek, south of road
		• top								[0.58±0.15, 1.69±0.23, 2.385±0.355]							
		• upper mudflow								2.43±0.07							
		• near base of exposure								120% modern							
		(b) sands:															
		• near top								4.83±0.64							
		• near base								1.64±0.21							
30	T30S, R21E Sec.1-3	Eolian deposit	Holocene	x	x	(x)				7.76±0.155							Lower Harts Draw
31	T30S, R21E, Sec.8-1	Eolian deposit	Holocene	x	x	(x)				Modern			<730				Indian Creek, fine-grained terrace
32	T30S, R21E, Sec.16-7	(a) Eolian deposit, over	Late Pleistocene		x			x						x			Gibson Dome, Indian Creek, 6-m terrace
		(b) Alluvial gravel	Late Pleistocene	ca 32	x	x	65–105	x	[1.96±0.2 "too inhomogeneous"] 124±13.5					x		x	
33	T30S, R21E, Sec.16-8	(a) Eolian deposit, over	Late Pleistocene		x			x									Gibson Dome, Indian Creek, 10-m terrace-1
		(b) Alluvial gravel	Late Pleistocene	ca 40	x	x	30–45	x	[106±13.37, 118±8.22]					x		x	
34	T30S, R21E, Sec.16-9	(a) Eolian deposit, over	Late Pleistocene		x	x		x	3.6±0.29					x			Gibson Dome, Indian Creek, 10-m terrace-2
		(b) Alluvial gravel	Late Pleistocene	ca 40	x	x	35–50	x	84.1±6.23					x		x	
35	T30S, R21E, Sec.16-5	(a) Eolian deposit, over	Late Pleistocene		x	x			4.01±0.31								Gibson Dome, Indian Creek, 12-m terrace-1
		(b) Alluvial gravel	Late Pleistocene	ca 50	x	x	125–205	x	100±8					x		x	

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 6 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	S[f]	Ages or Age Interpretation Based on Laboratory Analyses[b]: Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
36	T30S, R21E, Sec.16-4	(a) Eolian deposit:	Late Pleistocene		x	x		x						x			Gibson Dome, Indian Creek, 12-m terrace-2
		● Bca (0.2 m)							8.12±0.78								
		● 2B tca (0.5 m)							19.8±4.45								
		(b) Alluvial gravel	Late Pleistocene	≈ 50	x	x	50-65	x						x		x	
37	T30S, R21E, Sec.16-3	(a) Eolian deposit:	Late Pleistocene		x	x											Gibson Dome, Indian Creek, 20-m terrace-1
		● sandy silt: (0.3 m) (0.4 m)							215±16.6 "too inhomogeneous"								
		(b) Alluvial gravel	Late Pleistocene	≈ 80	x	x	60-100	x						x		x	
38	T30S, R21E, Sec.16-2	(a) Eolian deposit:	Late Pleistocene		x	x		x						x			Gibson Dome, Indian Creek, 20-m terrace-2
		● sandy silt: (0.15 m) (0.4 m)							204.2±24.43 163±12.4								
		(b) Alluvial gravel	Late Pleistocene	(≈ 80)	x		45-75	x						x		x	
39	T30S, R21E, Sec.16-1	(a) Eolian deposit, over	Late Pleistocene		x	x		x						x			Gibson Dome, Indian Creek, 32-m terrace
		(b) Alluvial gravel	Late Pleistocene	≈ 130	x	x	120-200	x	[140±9.7 "too inhomogeneous"]					x		x	
40	T31S, R19E, Sec.9-1	Eolian deposit:	Late Pleistocene		x	x	115-195										The Grabens, western dune
		● 2Bca soil (4.2 m)							51.56±4.67								
		● 3Bca soil (6.9 m)							65.37±4.57								
41	T31S, R19E, Sec.11-1	(a) Eolian deposit	Holocene		x	(x)		x									The Grabens, Cow Canyon, soil profile
		(b) Slopewash	Holocene		x	(x)		x		103% modern							
		(c) Fine-grained alluvium	Late Pleistocene		x	x	70-115	x	16.3±1.47	2.76±0.2							
42	T31S, R19E, Sec.11-2	Eolian deposit and fine-grained alluvium:	Holocene		x	(x)											The Grabens, Cow Canyon, swallowhole north of soil profile.
		● sandy silt: (3 m)								2.45±0.21							

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
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Locality(a)	Site (Township, Range, Section-Locality)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Type(d)	T(e)	S(f)	Pedogenesis: $CaCO_3$(g)	Clay(h)	TL(i)	^{14}C(j)	U-Th(k)	Amino Acid(l)	Paleomag(m)	Weathering(c): X	H	W	Comments
							Ages or Age Interpretation Based on Laboratory Analyses(b)										
43	T31S, R19E, Sec.14-1	Eolian deposit	Holocene (modern?)		x	(x)				"no charcoal"							The Grabens, burn area
44	T31S, R18E, Sec.14-2	Fine-grained alluvium:	Holocene		x	(x)											The Grabens, S. Cow Canyon. Three adjacent swallowholes (a, b, c)
		(a) • plant debris (3.5 m)								0.3±0.065							
		• sand (4.8 m)							3.22±0.29								
		• charcoal (5.1 m)								3.9±0.69							
		(b) • woody material (3.6 m)								110% modern							
		(c) • charcoal (3.7 m)								2.7±0.22							
45	T31S, R18E, Sec.28-1	(a) Fine-grained alluvium:	Holocene		x	(x)											Cross Canyon. Older deposits (b) have been cut and filled by younger alluvium (a)
		• woody material (1 m)								102% modern							
		• sand (2 m)							11.56±1.08								
		• charcoal (4.6 m)								6.42±0.73							
		• sand (4.6 m)							16.3±1.26								
		(b) Eolian deposits, over fine-grained alluvium:	Holocene or Late Pleistocene		x x	(x) (x)											
		• sand (1.5 m)							26.3±6.63								
		• charcoal (4 m)								1.02±0.52							
46	T31S, R21E, Sec.11-1	(a) Eolian deposit, over	Holocene		x	(x)	6-11			0.43±0.11							Gibson Dome, The Island
		(b) Alluvial gravel	Late Pleistocene	or 150	x											x	

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 9 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	E[f]	Pedogenesis: $CaCO_3$[g]	Pedogenesis: Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
47	T32S, R21E, Sec.10-2(s)	Fine-grained alluvium:	Holocene		x	(x)							<730				Gibson Dome, Cottonwood Creek. Older deposits (b) are cut and filled by (a)
		• charcoal (10.7 m)								0.72±0.55*[o]							*small sample, indicator age only; date is not considered reliable
	Sec.10-1(s)	Fine-grained alluvium:	Holocene		x	(x)							<730				
		• charcoal (3 m)								1.27±0.1							
		• charcoal (16.5 m)								1.6±0.1							
48	T32S, R23E, Sec.7-1	Fine-grained alluvium:	Holocene		x	(x)							<730				Harts Draw, north of road
		• charcoal (ca 7.5 m)								5.16±0.055							
49	T32S, R23E, Sec.7-2	Fine-grained alluvium	Holocene		x	(x)							<730				Harts Draw, at road crossing
50	T33S, R24E, Sec.32-1	(a) Eolian deposits, over	Holocene to Pleistocene		x	(x)											Monticello gravel pit
					x	x											
		(b) Alluvial gravel	Early to Mid-Pleistocene	ca 1500	x	x	470-780										
51	T34S, R14E, Sec.20-1	Lacustrine deposits:	Mid- to Late Pleistocene	ca 375													Abandoned Colorado River meander at Hite
		• snails										500 (+300,-200)					
52	T34S, R21E, Sec.27-1	Pack rat middens:															Allen Canyon Cave
		*(1) Douglas fir needles, twigs	Early Holocene		x					10.03±0.33							*midden number
		(1) Douglas fir wood	Early Holocene		x					[9.66±0.14 10.03±0.1]							
		(2) rat pellets	Mid-Holocene		x					7.2±0.09							
		(4) rat pellets	Late Holocene		x					1.82±0.05							
		(5) rat pellets	Late Holocene		x					3.0±0.07							
		(6) rat pellets	Late Holocene		x					3.4±0.06							
		(7) pine needles	Early Holocene		x					11.3±0.2							
		(8) rat pellets	Early Holocene		x					10.14±0.19							
		(3) Douglas fir needles, twigs	Early to Mid-Holocene		x					7.53±0.2							
		(9) rat pellets	Early Holocene		x					10.07±0.07							

Table I-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 5 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	C[f]	Ages or Age Interpretation Based on Laboratory Analyses[b]: Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
53	T36S, R22E, Sec.13-1	Alluvial gravel	Early to Mid-Pleistocene	ca 1125	x	x							>730				Johnson's Creek gravel pit
54	T36S, R22E, Sec.22-1	(a) Eolian deposit or fine-grained alluvium, over	Late Pleistocene		x												Blanding gravel pit, Pinenut Knoll
		(b) Alluvial gravel	Early to Mid-Pleistocene	ca 1250	x	x							>730				
55	T36S, R22E, Sec.24-1	(a) Eolian deposit, over	Mid- to Late Pleistocene		x	x								x			Blanding gravel pit
		(b) Alluvial gravel	Early to Mid-Pleistocene	ca 1000	x	x	880±1,445 (>730)								>730		
56	T37S, R18E, Sec.36-1	Fine-grained alluvium	Holocene	x	x	(x)				8.1±0.345							Kane Gulch
	T37S, R19E.																FR-2 drill site. *Localities 57 and 62 are combined into a single profile because of their close proximity. **No significant pedogenic carbonate has accumulated in these profiles.
57*	Sec.30-1	Eolian deposit	Late Pleistocene		x	x	75-125	x									
58	Sec.30-2	Eolian deposit	Late Pleistocene		x	x	55-95	x									
59	Sec.30-3	Eolian deposit	Late Pleistocene		x	(x)	**	x									
60	Sec.30-4	Eolian deposit	Holocene to Late Pleistocene		x	(x)	**	x									
61	Sec.30-5	Eolian deposit	Holocene to Late Pleistocene		x	(x)	**	x									
62*	Sec.30-6	Eolian deposit:	Late Pleistocene		x	x	75-125	x									
		■ sandy silt (0.6 m)							27.49±2.06								
		(1.7 m)							44.93±4.03								
63	T37S, R20E. Sec.11-3	Eolian or fine-grained alluvium:	Holocene to Late Pleistocene	x	x	(x)											Comb Wash. *^{14}C age assumed to calibrate amino acid data.
		■ Snail shells								12.5±0.16		*					

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 10 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	C[f]	Ages or Age Interpretation Based on Laboratory Analyses[b]: Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	Y	Comments
64	T37S, R20E, Sec.24-1	Fine-grained alluvium:	Holocene	x	x	(x)											Comb Wash. Snail layer is at base of 7-m-high terrace. Charcoal was found in a younger, 3-m-high fill terrace.
		• charcoal (0.8 m)	Late Holocene							0.41±0.06							
		• snails (6.5 m)	Late to Mid-Holocene									5±2					
65	T37S, R20E, Sec.30-1	Eolian deposits or fine-grained alluvium:	Late Pleistocene		x	x											Dry Wash, near old highway.
		• snails (6 m)										24±7					
66	T37S, R20E, Sec.31-1	Eolian deposits or fine-grained alluvium:	Late Pleistocene		x	x	115-195*	x		x							Tributary to Dry Wash. *Excessive accumulation of $CaCO_3$; may be stream deposited, in part.
		• snails (2.1-2.6 m)										19±5					
67	T37S, R20E, Sec.31-3	(a) Fine-grained alluvium:	Late Holocene	x	x	(x)											Dry Wash. (a) is younger fill terrace. Surface is ca 2 m lower than (b).
		• charcoal (1.2 m)								2.38±0.09							
		• sand (1.3 m)							3.69±0.31								
		(b) Fine-grained alluvium:	Mid-Holocene	x	x	(x)											
		• carbonaceous soil (1.2 m)								[9.49±0.09 7.84±0.7 "insufficient sample"]							*Older ^{14}C age assumed from (b). Used to calibrate amino acid data from other sites.
		• snails (1.2 m)										*					
		• sandy silt (1.8 m)							7.05±0.64								

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 11 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	R[e]	P[f]	Ages or Age Interpretation Based on Laboratory Analyses[b]: Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
68	T37S, R21E, Sec.3-1	Fine-grained alluvium:	Holocene	x	x	x							<730				Cottonwood Wash
		• charcoal (3.9 m)								1.75±0.06							
		• charcoal (6.9 m)								3.07±0.325							
		• sandy silt (6.9 m)							59.1±6.78								
69	T37S, R21E, Sec.14-1	(a) Eolian deposit, over	Holocene		x	(x)									x		Zeke's Hole, gravel pit
		(b) Alluvial gravel	Late Pleistocene	ca 75	x	x									x		
70	T37S, R21E, Sec.15-1	Alluvial gravel	Mid- to Late Pleistocene	ca 210	x	x					34±3 probable; 74±8 maximum						Gravel terrace west of Zeke's Hole.
71	T37S, R22E, Sec.32-1	Eolian deposit:	Early(?) to Late Pleistocene	ca 1000*	x	x	55-95	x						x			White Mesa, backhoe pit
		• sandy silt: (0.4 m)							24.41±2.3								*Surface appears correlative with surface formed on deposits at Locality 55.
		(2.25 m)							32.7±2.95								
72	T37S, R22E, Sec.33-1	Eolian deposit or fine-grained alluvium:	Early(?) to Late Pleistocene	ca 1000*	x	x	335-560	x						x			White Mesa, bulldozer trench
		• sandy silt: (1.1 m)							45.7±3.95								*Surface appears correlative with surface formed on deposits at Locality 55.
		(2.1 m)							93.8±7.02								
		(3.0 m)							137±10.9								
73	T38S, R11E, Sec.9-1	Alluvial gravel	Early Pleistocene	ca 800	x	x							>730(?)				Bullfrog Basin, Lake Powell
74	T38S, R11E, Sec.32-1	Alluvial gravel	Early Pleistocene	ca 820	x	x			307±39.3								Halls Crossing, Lake Powell

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 12 of 14)

			Estimated Age, Basis				Ages or Age Interpretation Based on Laboratory Analyses[b]							Weathering[c]			
							Pedogenesis										
Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Age	Topo[d]	r[e]	c[f]	$CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	X	H	W	Comments
75	T38S, R11E, Sec.33-1	Eolian deposits	Holocene or Late Pleistocene		x	x							<730				Garbage pit near Halls Crossing
76	T38S, R11E, Sec.35-1	Eolian or fine-grained alluvium	Early Pleistocene	ca 1000	x	x			140±11.8								Halls Crossings, Lake Powell
77	T38S, R20E, Sec.5-1	Eolian or fine-grained alluvium	Holocene or Late Pleistocene	x	x	x							<730				Dry Wash
78	T38S, R20E, Sec.12-3	Eolian deposit or fine-grained alluvium:	Early Holocene or Late Pleistocene	x	x x	x											Hole Canyon. Older fluvial sediments (containing c) are cut by channel (b is near base). Both are draped by deposits containing a.
	(a)	• charcoal • snails	(Early Holocene)		x	(x)				9.55±0.08		ca 11					
	(b)	• snails (3 m below a)	(Late Pleistocene?)		x		x					ca 11					
	(c)	o snails (6 m below a)	(Late Pleistocene)		x	x						ca 18 - 28					
79	T38S, R20E, Sec.25-1	Fine-grained alluvium: • snails	Pleistocene	x	x	x						ca 11; ≥9, ≤30					Tributary to Comb Wash.
80	T38S, R22E, Sec.31-1	Alluvial gravel	Late Pleistocene	ca 90	x	x									x		Cottonwood Wash, 20-m terrace
81	T39S, R21E, Sec.6-1	Pack rat middens:	Holocene to Late Pleistocene			x											Fishmouth Cave *midden number
		*(1) Limber pine needles, etc.								12.77±0.14							
		(2) Rat pellets								10.36±0.08							
		(2) Douglas fir needles, etc.								9.34±0.29							
		(3) Douglas fir needles, etc.								10.54±0.18							
		(3) Utah juniper twigs, etc.								2.79±0.1							

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Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 13 of 14)

Locality[a]	Site (Township, Range, Section-Outcrop)	Deposit/Sample Description (depth)	Estimated Age, Basis: Age	Topo[d]	T[e]	C[f]	Ages or Age Interpretation Based on Laboratory Analyses[t] — Pedogenesis: $CaCO_3$[g]	Clay[h]	TL[i]	^{14}C[j]	U-Th[k]	Amino Acid[l]	Paleomag[m]	Weathering[c]: X	H	W	Comments
81 (cont.)		(4) Utah juniper twigs, etc.								6.1±0.1							
		(5) Utah juniper twigs, etc.								9.7±0.11							
		(6) Utah juniper twigs, etc.								3.55±0.06							
		(7) Utah juniper twigs, etc.								3.74±0.07							
		(9) Utah juniper twigs, etc.								2.26±0.09							
82	T39S, R21E, Sec.24-1	Eolian, or fine-grained alluvium	Early Pleistocene	ca 1000	x	x	770-1285										No Man's Island
83	T40S, R22E, Sec.19-1-1	Alluvial gravel	Mid- to Early Pleistocene	ca 625	x	x					121±9 probable and maximum						Bluff gravel pit San Juan River deposits.
Animas River Study																	
84	T29S, R12W, Sec.20-1	(a) Colluvial deposit, over	Late Pleistocene	ca 150	x	x									x		Terrace east of Farmington
		(b) fine-grained alluvium													x		
85	T29S, R13W, Sec.8-1	(a) Eolian deposits, over	Late Pleistocene	ca 325	x	x									x		Farmington Airport terrace
		(b) alluvial gravel			x	x									x		
86	T33N, R9W, Sec.5-1	(a) Eolian deposit, over	Late Pleistocene		x	x									x		Florida Mesa. *Deposit contains Lava Creek Ash (dated at 620,000 years).
		(b) Eolian deposit*, over	Mid-Pleistocene														
		(c) Alluvial gravel	Early Pleistocene	ca 560													

Note: Measurements in this table are given in meters only. To convert meters to feet, multiply by 3.281.

(a) See Figure 1-1 for map of localities.
(b) Ages given in 1,000s of years.
(c) Relative weathering age assessments were made at localities indicated with an x. X = X-ray analysis. H = heavy mineral analysis. W = weathering rind measurements (Section 4.1.7).
(d) Topo = Topographic setting. Age estimates (x1,000 years) are based on an estimated long-term incision rate of 0.24 m/1,000 years. x = topographic position provided a qualitative estimate of age. See Section 4.1.8.

Table 1-1. Geologic Age Data Collected at Localities in the Paradox Basin, Utah
(Page 14 of 14)

(e) T = texture and/or cementation of soil and/or deposit. x = qualitative age estimate.
(f) C = pedogenic carbonate morphology, as described in Section 4.1.1. x = qualitative age estimate. (x) signifies lack of calcic soil development.
(g) $CaCO_3$ = accumulation of pedogenic carbonate in soil profile. Age (x1,000 years) based on a carbonate accumulation rate of 0.15 g to 0.25 g/cm^2/1,000 years (Section 4.1.1).
(h) x = particle size distribution in soil profile was analyzed.
(i) TL = thermoluminescence analysis. Laboratory numbers are given in Table 4-8 (Section 4.1.3).
(j) ^{14}C = radiocarbon analyses. Age given in 1,000 years before present (BP). Laboratory numbers for samples are given in Table 4-6 (Section 4.1.2).
(k) U-Th = Uranium-series analysis (Section 4.1.6).
(l) Amino acid analysis. Laboratory numbers given in Table 4-11 (Section 4.1.4). x = amino acids in soils measured; no interpreted date.
(m) Paleomag = paleomagnetic analysis. Age estimates based on normal (<730,000 years) paleomagnetic signature or reversed (>730,000 years) paleomagnetic signature. Laboratory numbers given on Figures 4-3 and 4-4 (Section 4.1.5).
(n) Brackets denote duplicate or triplicate dates.
(o) For starred entries, see comments column to the right.

2.0 HOLOCENE PALEOCLIMATE STUDIES

Potential climatic trends are of interest to repository studies because of their possible effect on ground-water recharge and flow, and on the rate at which geomorphic processes are occurring. Major periods of widespread glaciation occurred in the Rocky Mountain region throughout Pleistocene time. In the Paradox Basin, coarse-grained pre-Holocene fluvial deposits and buried soils (WCC, 1982a, Vol. I, pp. 3-23 to 3-25) attest to the occurrence of these periodic climatic changes. The most recent major change from a cool, wet, late Pleistocene climate, which is associated with mountain glaciation in the western United States, to conditions that resemble the present-day environment occurred approximately 11,000 to 8,000 years ago (Spaulding et al., 1983; Baker, 1983; Betancourt, 1984). Although rainfall and temperature since then have varied, no changes during the Holocene period (the last 10,000 years) have been as large as those accompanying a major glacial ice advance and retreat.

Initial Quaternary studies for the Paradox Basin Project focused on pre-Holocene fluvial terrace deposits resulting from glacial and periglacial activity at the headwaters of streams in the study area (WCC, 1982a). Streams draining the Abajo, La Sal, and Henry Mountains received large sediment loads as a result of this activity. This led to the development of nested gravel terraces in the downstream portions of the stream valleys. The Pleistocene deposits consist primarily of gravel clasts and boulders, and are clearly distinct from the overlying fine-grained deposits that are interpreted to be representative of Holocene fluvial depositional regimes. The youngest dates derived from the gravel deposits, based on thermoluminescence (TL) analyses of fine-grained material separated from a gravel matrix, are 9,300 and 17,700 years before present (BP) (Section 4.1.3). However, as discussed in Section 4.1.3, the samples may have been contaminated by younger eolian silt that had filtered down into the gravel horizon where the samples were collected.

The studies reported in this chapter are focused on the Pleistocene/Holocene transition period and on climatic fluctuations that occurred during Holocene time. Methods that are particularly useful for studying paleoclimates of this age range include examination of (1) paleovegetation incorporated into dateable late Pleistocene and Holocene pack rat middens, (2) pollen records from bogs or lakes, and (3) fossil mollusk assemblages in sedimentary deposits. Paleoclimatic data can also be interpreted from the sedimentologic character of fluvial deposits, which record recognizable stream regime changes that may be climate-related.

All these methods were preliminarily used in the Paradox Basin studies to determine if the methods were feasible and useful. The contents of pack rat middens collected from two caves in the Elk Ridge area were analyzed; and a shallow core, collected from the shore of a natural lake, Duck Lake, in the Abajo Mountains, was examined for pollen. Several samples were collected to date and correlate stratigraphic units in Salt Creek and in Canyonlands National Park to assess if sedimentologic changes may have been climatically controlled. Finally, snails collected from stream deposits, primarily in the Elk Ridge area, were identified and interpreted for their environmental sensitivity.

2.1 PRESENT CLIMATIC SETTING

Most of southeastern Utah has a warm, semiarid climate at present. Arid conditions prevail along canyon bottoms and on the plateaus, and cooler, more humid conditions occur in the higher portions of the La Sal and Abajo Mountains. Three sources of moist air are important in producing precipitation in southeastern Utah:

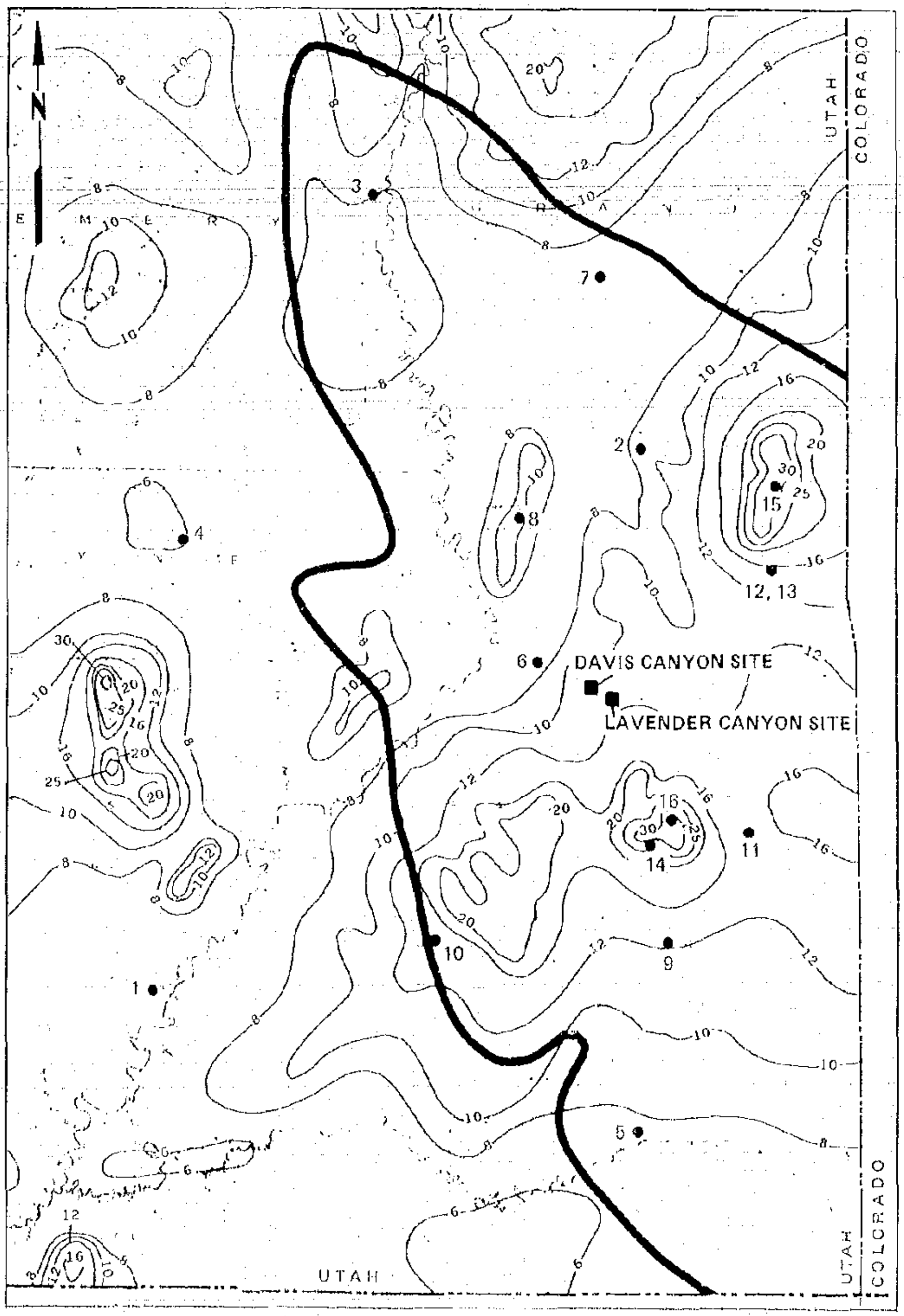
1. During the winter months, Pacific frontal storms bring rain and snow to the area as the storms move eastward from the Pacific Coast to the Rocky Mountains. The normal track of these winter storms is north of the Paradox Basin, so the resulting precipitation in the area is relatively low.

2. Precipitation during the late summer months (July-September) is the result of intense convectional storms whose principal moisture source is warm, moist air carried northwest from the Gulf of Mexico. The Paradox Basin is presently near the northwestern limit of influence for Gulf moisture.

3. During late summer, moist maritime air may also be carried into southeastern Utah from the Gulf of California (Betancourt and Biggar, 1985). Much of the summer precipitation in the area occurs as localized thunderstorms caused by convection over the intensely heated desert areas and orographic uplift over the La Sal and Abajo Mountains.

The average annual precipitation in southeastern Utah ranges from less than 150 mm (6 in) to over 760 mm (30 in) (Figure 2-1; Table 2-1). Areas lower than approximately 2,130 m (7,000 ft), which constitute most of the region, have annual precipitation totals of less than 355 mm (14 in) (Figure 2-1). Precipitation is highest in the La Sal and Abajo Mountains, where areas above approximately 2,740 m (9,000 ft) receive more than 635 mm (25 in) per year. Salt Valley and the low-lying areas adjacent to the Colorado, Green, and San Juan Rivers have annual precipitation values that are less than 200 mm (8 in). The lowest precipitation values are recorded at Green River (152 mm [6 in]) and Hanksville (135 mm [5.3 in]) (Table 2-1) in the Green River Desert.

The mean annual temperatures in portions of southeastern Utah below 2,130 m (7,000 ft) range from 7.6 to 15.0°C (45.7 to 58.9°F) (Table 2-2). Summer temperatures in excess of 37.8°C (100°F) are common at elevations less than approximately 1,830 m (6,000 ft). Subfreezing temperatures commonly cause winter precipitation to fall as snow throughout the region. Snowpack in the La Sal and Abajo Mountains is a significant source of spring runoff in streams such as Pack Creek, Indian Creek, Cottonwood Creek, and Cottonwood Wash.



LEGEND:

Boundary of Paradox Basin in Utah

—12— Isopleth of annual precipitation, in inches

2 ● Weather station; listed in Tables 2-1 and 2-2

Source: Butler and Marsell, 1972

0 20 40 mi

0 20 40 km

LOG 1596
REV. 1—4/5/82

AVERAGE ANNUAL PRECIPITATION
LOCATION OF WEATHER STATIONS,
SOUTHEASTERN UTAH

Quaternary Topical Report

Project No. 17000
Woodward-Clyde Consultants

Figure 2-1

Table 2-1. Mean Annual Precipitation at Selected Monitoring Stations in the Paradox Basin

Station[a]	Station No. on Fig. 2-1	Elevation Meters	Elevation Feet	Period of Record Used	Number of Years of Data[b]	Average Precipitation[c] mm	Average Precipitation[c] in	1966-1980 Average Stations With ca 50-yr Record[d] mm	1966-1980 Average Stations With ca 50-yr Record[d] in
Bullfrog Basin	1	1,165	3,822	1968-1980	13	158	6.24		
Moab 4NW	2	1,208	3,965	1931-1980	46	214	8.42	215	8.48
Green River	3	1,240	4,070	1931-1980	52	152	5.97	150	5.92
Hanksville	4	1,313	4,308	1931-1980	48	135	5.31	143	5.62
Bluff	5	1,315	4,315	1931-1980	50	198	7.81	207	8.15
Canyonlands, The Needles	6	1,536	5,040	1966-1980	15	212	8.35		
Thompsons	7	1,570	5,150	1931-1980	42	222	8.75	230	9.07
Canyonlands, The Neck	8	1,798	5,900	1966-1980	15	216	8.50		
Blanding	9	1,868	6,130	1931-1980	50	304	11.96	306	12.03
Natural Bridges Nat'l. Monument	10	1,981	6,500	1966-1980	15	298	11.73		
Monticello	11	2,079	6,820	1931-1980	47	360	14.19	373	14.70
La Sal "A"	12	2,125	6,975	1930-1962	24	326	12.85		
La Sal "B"	13	2,048	6,720	1964-1981	15	343	13.51		
Camp Jackson[e]	14	2,804	9,200	1959-1980	13	704	27.70		
La Sal Mtns. Upper[e]	15	2,865	9,400	1959-1980	16	728	28.66		
Buckboard Flat[e]	16	2,865	9,400	1957-1980	20	780	30.69		

(a) Station operated by U.S. Dept. of Commerce, unless otherwise noted. Sources of data: U.S. Department of Agriculture (1930); U.S. Department of Commerce (1965; 1960-1981); Soil Conservation Service (1978).
(b) Annual totals are unavailable for some years at some stations.
(c) Averages calculated for water years, October 1 - September 20.
(d) These 15-year averages are included for long-term stations for better comparison with more recently installed stations. In general, precipitation for 1966-1980 was slightly greater than that for 1931-1980.
(e) Station operated by Soil Conservation Service, Salt Lake City.

Table 2-2. Mean Annual Temperature at Selected Monitoring Stations in the Paradox Basin

Station	Station No. on Fig. 2-1	Elevation Meters	Elevation Feet	Period of Record Used	Number of Years of Data	Average Temperature °C	Average Temperature °F
Bullfrog Basin	1	1,165	3,822	1971-1980	10	15.0	59.0
Moab 4NW	2	1,208	3,965	1962-1979	15	13.5	56.3
Green River	3	1,240	4,070	1961-1975	13	10.9	51.6
Hanksville	4	1,313	4,308	1961-1980	20	11.5	52.7
Bluff	5	1,315	4,315	1962-1980	18	11.7	53.0
Canyonlands, The Needles	6	1,536	5,040	1966-1980	12	11.6	52.8
Thompsons	7	1,570	5,150	1961-1980	13	11.3	52.3
Canyonlands, The Neck	8	1,798	5,900	1966-1980	11	11.6	52.9
Blanding	9	1,868	6,130	1961-1980	20	9.8	49.6
Natural Bridges Nat'l Monument	10	1,981	6,500	1967-1980	9	10.5	50.9
Monticello	11	2,079	6,820	1961-1980	20	7.6	45.7
La Sal "B"	13	2,126	6,975	1969-1980	10	8.2	46.8

Note: Stations operated by U.S. Department of Commerce. Data are published in annual summaries of climatological data for Utah (U.S. Dept. Commerce, 1960-1981).

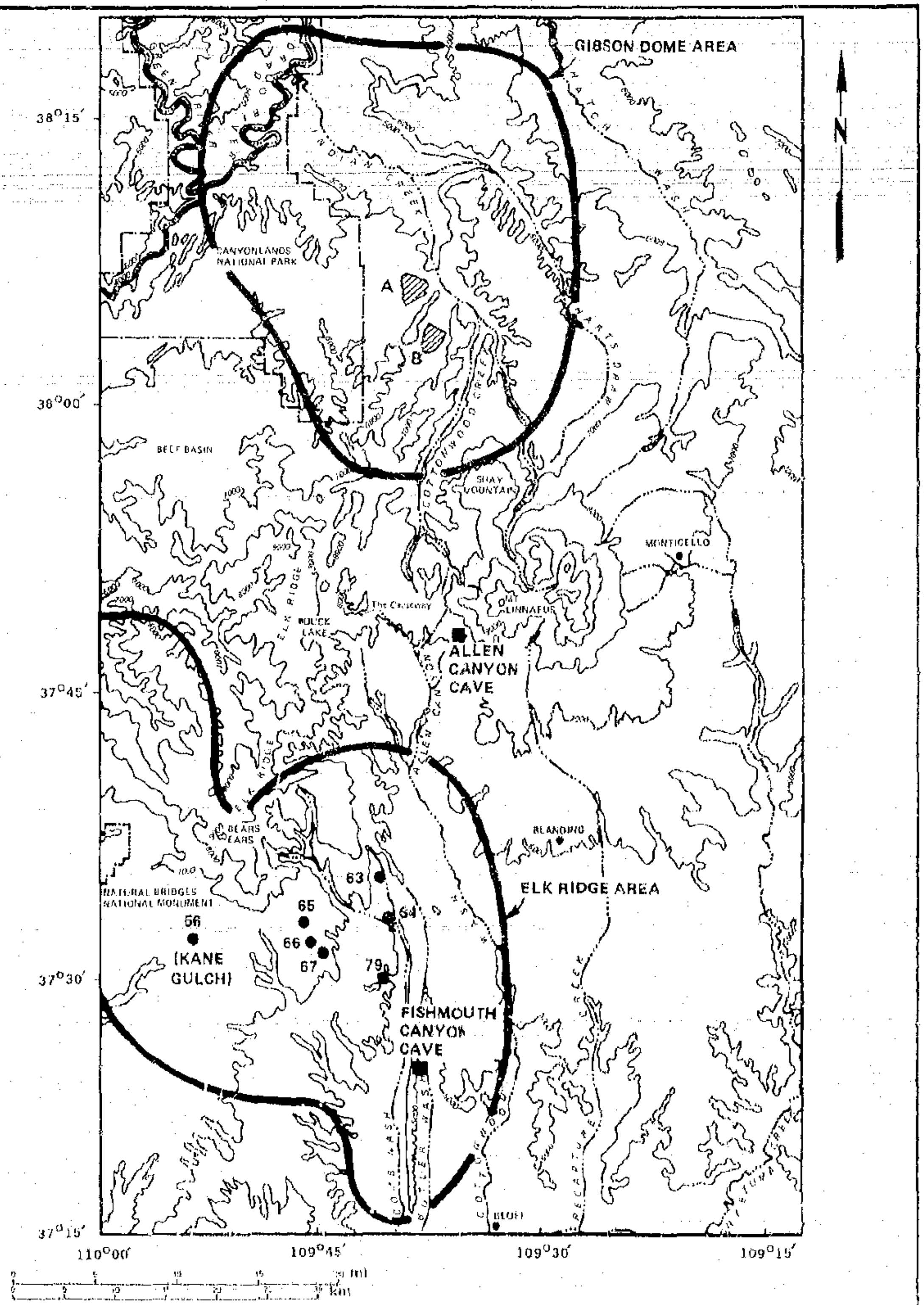
2.2 PACK RAT MIDDENS

In the last 20 years, fossilized pack rat middens have been used as a prime information source for paleoenvironmental conditions in the American Southwest (Spaulding et al., 1983; Van Devender and Spaulding, 1979; Wells and Jorgensen, 1964). Middens are the remains of pack rat shelters and refuse piles, and consist of plant material and pack rat fecal pellets cemented with crystallized and rehydrated urine. Plant debris incorporated in the midden can usually be identified to the species level, and organic debris is usually sufficient to obtain a reliable radiocarbon date. It is therefore possible to reconstruct, in considerable detail, the vegetation growing within approximately 100 m (300 ft) of the fossil midden (the collecting radius of a pack rat) at a specific time in the past (Betancourt, 1984).

In order to determine whether middens of late Pleistocene age are preserved in the area, and whether useful paleoclimatic data could be interpreted from those middens, a preliminary study was conducted by WCC during late 1982 and 1983. The results of the study were reported by Betancourt and Biggar (1985) and are summarized here.

Two caves that contained middens spanning the last 13,000 years were found in cliff exposures of the Navajo Sandstone on the south flank of the Abajo Mountains, west of Blanding, Utah (Figure 2-2). Using modern vegetation zones in the Abajo Mountains as an analog, the midden data indicate that a 700 to 850-m (2,300 to 2,800-ft) depression of the current elevational range of spruce-fir and limber pine-Douglas fir plant communities had occurred by latest Pleistocene time (13,000 to 11,000 years BP), suggesting that the local climate was cooler and wetter than at present. Using weather data collected during the last 20 years in the Four Corners area, the plant communities represented in the latest Pleistocene middens are today growing in locations having mean annual temperatures 3 to 4°C (5.5 to 7°F) cooler than current temperatures at the collection sites, and a mean annual precipitation 35 to 115 percent greater than the current estimated precipitation at the collection sites (Table 2-3). The occurrence of yucca and prickly pear in the latest Pleistocene Fishmouth Cave middens indicates that temperatures at that time and location could not have been more than 5°C (9°F) cooler than they are today. Moreover, plants that grow in response to summer precipitation are absent at both cave sites, suggesting that rainfall was concentrated in the winter months.

Similar lowering of vegetation zones during the late Pleistocene has been documented elsewhere on the Colorado Plateau and in the Great Basin. Spruce macrofossils have been found in sediments dated between 13,000 and 11,000 years BP at Cowboy Cave, 56 km (35 mi) northwest of Davis Canyon (Spaulding and Petersen, 1980). During the full glacial period (21,000 to 15,000 years BP) in the eastern Grand Canyon, several conifers grew at elevations 600 to 1,000 m (1,970 to 3,250 ft) lower than they do today (Cole, 1982). At Canyon de Chelly (1,770 m [5,800 ft]) in northeastern Arizona, a pack rat midden dated at 11,900 years BP records blue spruce, limber pine, dwarf juniper, and Douglas fir (Betancourt and Davis, 1984). Limber pine no longer occurs in the nearby Chuska Mountains, which reach an elevation of approximately 2,740 m (9,000 ft).



Legend:

A Davis Canyon Site

B Lavender Canyon Site

Contour Interval - 1,000 feet

LOG 2048
REV. 2 - 8/21/85

LOCATION OF BIOSTRATIGRAPHIC AND PACK RAT MIDDEN STUDY SITES

Quaternary Topical Report

Project No. 17000
Woodward-Clyde Consultants

Figure 2-2

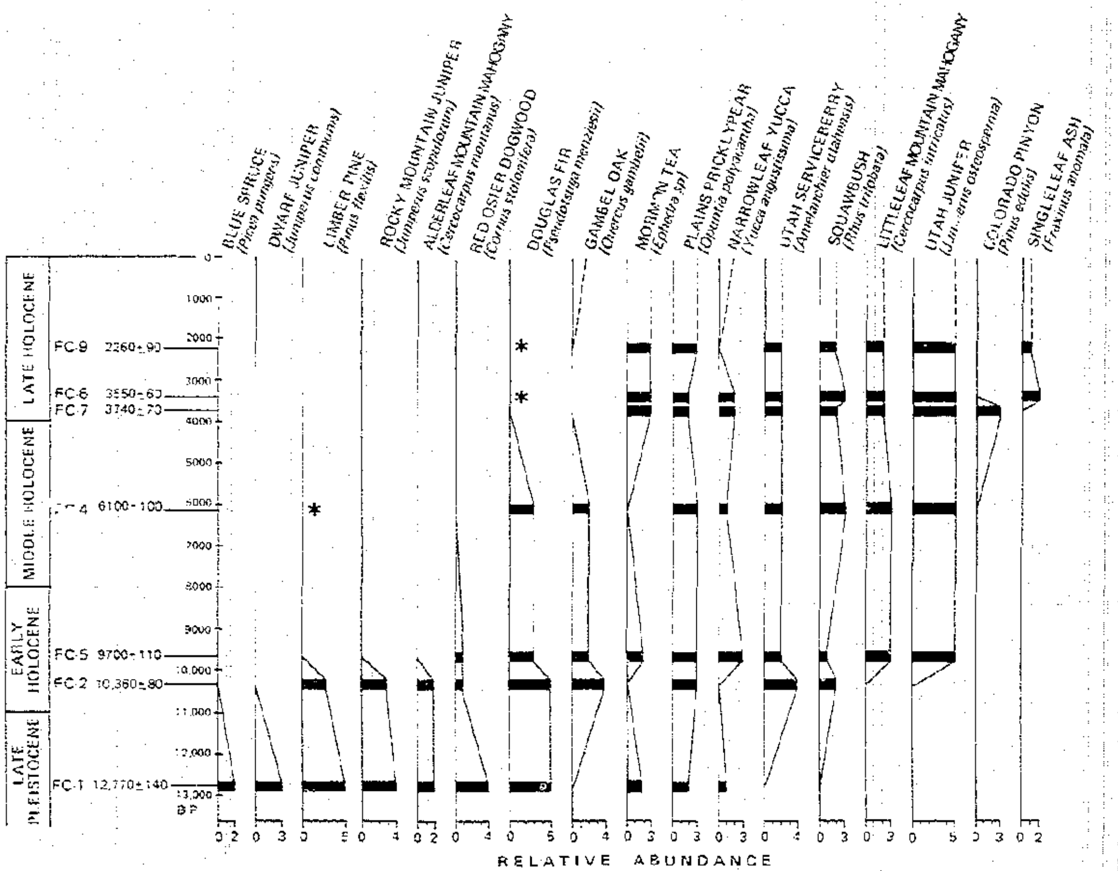
Table 2-3. Predicted Present and Latest Pleistocene Climates at Fishmouth and Allen Canyon Caves, Utah

Location	Elevation m	Elevation ft	Mean Annual Precipitation mm	Mean Annual Precipitation in	Mean Annual Temperature °C	Mean Annual Temperature °F
FISHMOUTH CAVE						
Present	1,585	5,200	208-232	8.2-9.1	11.1	52
Latest Pleistocene Analog	2,440	8,000	377-496	14.8-19.5	7.2	45
Implied Change			+169-264	+6.7-10.4	-3.9	-7
Percent Change			+82-114			
ALLEN CANYON CAVE						
Present	2,195	7,200	335-379	1.32-14.9	8.3	46.9
Latest Pleistocene Analog	2,895	9,500	455-787	17.9-31.0	5.1	41.2
Implied Change			+119-408	+4.7-16.1	-3.2	-5.7
Percent Change			+36-100			

Source: Betancourt and Biggar (1985).

The early Holocene (11,000 to 8,000 years BP) on the Colorado Plateau appears to have been a time of rapid change in vegetation. Middens at both cave sites record the transition from a late Pleistocene vegetation assemblage dominated by alpine species, to the modern-day flora. At Fishmouth Cave (elevation 1,585 m [5,200 ft]), which is located in a desert scrub zone, the major change had occurred by approximately 10,000 years BP (Figure 2-3). New arrivals in the early Holocene at Fishmouth Cave included Gambel oak and Utah juniper.

At Allen Canyon Cave (elevation 2,195 m [7,200 ft]), where the age control is less precise, the change occurred between 10,030 and 7,200 years BP (Figure 2-4). A similar change occurred between 9,500 and 8,300 years BP at Chaco Canyon (Betancourt et al., 1983), which is intermediate in elevation (1,920 m [6,300 ft]) between Fishmouth Cave and Allen Canyon Cave. Plants associated with summer precipitation and relatively high annual temperatures (e.g., Gambel oak, ponderosa pine, Colorado pinyon, one-seed juniper, Utah juniper) began arriving at the three sites at approximately 10,000 years BP.



FISHMOUTH CAVE, San Juan County, Utah
37°25′45″N, 109°39′00″W
ELEV 1585 m (5200 ft)

* *PROBABLE CONTAMINANTS*

FROM BETANCOURT and BIGGAR, 1985

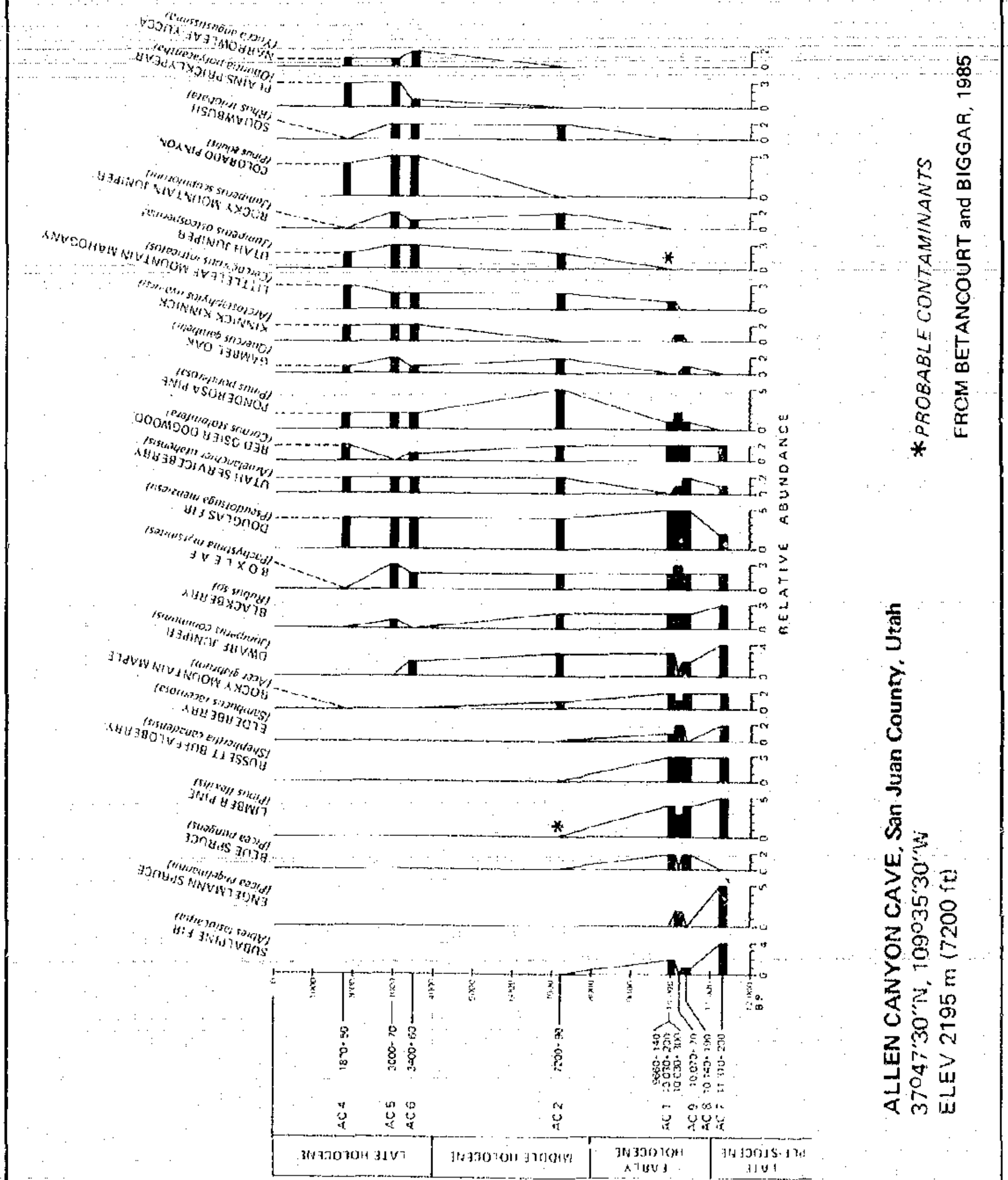
LOG 1468
REV.0--6/28/83

SERIATED CHRONOSEQUENCE SHOWING RELATIVE ABUNDANCE OF SELECT PLANT MACROFOSSILS

FISHMOUTH CAVE STUDIES
Quaternary Topical Report

Project No. 17000
Woodward-Clyde Consultants

Figure 2–3



SERIATED CHRONOSEQUENCE SHOWING RELATIVE ABUNDANCE OF SELECT PLANT MACROFOSSILS, ALLEN CANYON CAVE STUDIES

Quaternary Topical Report

LOG 1469 REV.0–6/28/83	Project No. 17000 Woodward-Clyde Consultants	Figure 2–4

Pinyon-juniper woodland and sagebrush parkland characterize the present-day vegetation at this site.

The cooler, wetter latest Pleistocene climate can be attributed to a southward shift of the polar jet stream and middle latitude storm track during the time of global cooling (Barry, 1983; Spaulding et al., 1983). The subsequent widespread shift of vegetation zones to higher elevations at the beginning of Holocene time may be related to the return of the jet stream to its present position by 8,000 years BP, resulting in an increase in mean summer and annual temperatures, a shift from winter-dominated to summer-dominated rainfall, and a decreasing frequency of spring freezes.

Global climate fluctuations have continued through the Holocene, but they have been more subtle than the change that marked the end of the Pleistocene. In the American Southwest, temperatures were generally warmer during the middle Holocene (8,000 to 4,000 years BP) than today (Antevs, 1955; Baker, 1983). Antevs' (1955) concept of a hot-dry "Altithermal" during this time may be true for the northern Great Basin, where the theory was formulated. However, as Martin (1963) speculated, warmer conditions may have enhanced the effectiveness of summer monsoons south and east of the Great Basin, which would include southeastern Utah. Therefore, this increase in temperature may have been accompanied by an increase in precipitation, which would encourage the observed northward migration of Gambel oak.

The distribution of Gambel oak during late Holocene time (4,000 years BP to present) suggests a cooling trend, which may be attributed to greater effective moisture. However, this trend may also have been accompanied by a decrease in summer rainfall. The arrival of prickly pear and yucca at Allen Canyon Cave by 3,400 years BP indicates greater aridity at that site after the middle Holocene.

This preliminary study of pack rat middens proved the presence of latest Pleistocene middens in the area, and indicated that useful information on the magnitude and timing of paleoclimatic changes can be acquired from the middens. Both sites provided a detailed biochronology covering approximately the last 13,000 years, and the data indicate synchronous vegetational changes (with the elevational differences taken into consideration) at both sites. The overall pattern of paleoclimatic change, as interpreted from the fossil plant debris, is also similar to that observed elsewhere in the Southwest.

Although this pilot study was successful in collecting useful data, it does not draw upon a large data base, particularly for making regional interpretations of paleotemperatures and precipitation. Collection of middens from additional sites is recommended to (1) lessen the effect of any microclimatic control of the midden record from one site; and (2) verify that the large-scale paleoclimatic changes that occurred on the north side of the Abajo Mountains, where the Davis and Lavender Canyons potentially acceptable repository sites are located, are comparable to the climatic parameters defined to the south during this preliminary study.

2.3 POLLEN STUDIES

Pollen separated from a sedimentary sequence, particularly from deposits that have accumulated in a bog or lake, has been used extensively throughout the world to reconstruct past plant assemblages and thereby interpret climatic conditions or cultural changes. In the arid setting of the Paradox Basin, natural lakes or bogs are commonly confined to the glaciated areas of the La Sal and San Juan Mountains. No evidence of glaciation in the Abajo Mountains, which are closest to the Gibson Dome study area, has been previously documented (Witkind, 1964), and none was observed during the current Paradox Basin studies.

Although glaciation has not been documented in the Abajo Mountains, one small lake was observed in the area. Duck Lake (Figure 2-2) lies at an elevation of 2,650 m (8,700 ft) and has a maximum water depth of approximately 1 m (3 ft). Examination of aerial photographs revealed small circular grassy areas nearby that may also have been ponds at one time. The lake probably represents a dissolution feature in the sandstone bedrock surface. This is the origin ascribed by Wright (1964) to similar features observed in the Chuska Mountains in northwestern New Mexico.

2.3.1 Previous Studies

Only limited pollen data have been collected in the Four Corners area of the Colorado Plateau. West (1978) sampled a 5.4-m (17.7-ft)-thick alluvial sequence exposed in Kane Gulch in the western part of the Elk Ridge study area (Figure 2-2). Only one radiocarbon date, 7,385±80 years BP (Salkin, 1975, WIS-742; West, 1978), derived from a sample collected approximately 1 m (3 ft) above the base of the deposits, was available for estimating the age of the deposits. A comparable date of 8,100±345 years BP (DIC-2064 [see Section 4.1.2]; Locality 56, Table 1-1) was obtained when the deposits were redated during the present studies.

The pollen collected by West (1978) from Kane Gulch was poorly preserved, and it proved difficult to obtain a minimum count of 200 grains, particularly below an erosional unconformity at a depth of 1.3 m (4.3 ft). The upper zone of the sequence contained pollen resembling the present vegetation cover in the area, whereas the pollen profile below the unconformity was significantly different, and was dominated by a relatively high *Pinus* (pine) value, suggesting that more effective moisture characterized that depositional period (West, 1978). However, because pine pollen is preferentially preserved in an oxidizing environment, such as an ephemeral stream bed prior to subsequent burial (Hall, 1977), the predominance of *Pinus* pollen in the lower part of the Kane Gulch section may be a result of its resistant character rather than paleoclimatic conditions.

In another study, Lindsay (1976) described pollen retrieved from the Pint-Size Shelter archaeological site in Castle Valley, Utah, west of the San Rafael Swell, and 130 km (82 mi) west of Moab. Although it was eroded and poorly preserved, the pollen associated with the Archaic occupation (between ca 4,500 to 3,400 years BP) indicated a slightly drier climate than at present. During the later Fremont occupation (ca 1,800 years BP), vegetation was not significantly different from today's at that location. Currey (1976) interprets the periods of eolian deposition as being caused by a reduction in winter precipitation, intensified summer convective precipitation events, and relatively low available soil moi ture. This would result in high sediment yields in streams, and would also provide a source for windblown material.

Paleoclimatic conditions were interpreted from the pollen record in alluvial deposits at Chaco Canyon, northwestern New Mexico, by Hall (1977). Hall inferred that the full glacial vegetation present at 10,000 years BP altered to a pinyon woodland 7,000 years BP during a warm and moderately dry postglacial period; the greatest time of aridity occurred between 5,600 and 2,400 years BP. He interpreted the vegetation at Chaco Canyon between 7,000 and 5,000 years BP to be similar to that of the present landscape. The abundance of ponderosa pine increased significantly between 2,200 and 1,000 years BP, indicating an increase in effective moisture at the higher elevations during that time. However, the amount of precipitation increased only slightly at Chaco Canyon until 850 to 600 years ago, when it increased almost to present-day amounts. This increased precipitation resulted in a spread of pinyon woodland and the abandonment of the Anasazi pueblo after local streams became entrenched below the distribution canals of the Anasazi irrigation system. Ponderosa and pinyon pine pollen has continued to increase during the last 100 years, suggesting increased precipitation at both high and low elevations.

2.3.2 Current Studies

The apparent lack of traditional pollen traps in the form of lakes or bogs close to the Gibson Dome area required the consideration of other potential traps that might preserve pollen. Eolian deposits, which are abundant throughout the Paradox Basin and may be pre-Holocene in age, were therefore considered. Researchers have generally agreed that pollen could not be preserved in such oxidizing conditions, and that only a few resistant species could withstand the high pH (8.5) of Southwest environments (West, 1978; Hall, 1977). Nonetheless, two samples of eolian deposits previously collected in the Elk Ridge area were sent to the University of Kansas in early 1982 for analysis. The samples were found to contain moderate amounts of rather well preserved pollen; however, because the samples had originally been collected for soil analyses, the observed pollen probably consisted of fossil pollen contaminated with modern pollen from the surface of the exposure. With better sampling methods, uncontaminated samples that provide data on paleovegetation and its temporal variations could probably be derived from the eolian deposits (Johnson, 1982).

Pollen assessment activities were also conducted at Duck Lake, a small lake that occupies a sandstone dissolution feature at 2,650 m (8,700 ft) in the Abajo Mountains. Samples were collected on the edge of the lake using a soil probe mounted on a hand auger. These were sent to the University of Arizona in Tucson to determine whether pollen is present in the lake sediments, and whether any significant changes can be seen in the pollen assemblage with depth. Three subsamples were examined from (1) near the ground surface (SURF), (2) a depth of approximately 35 cm (14 in) (B MID), and (3) the bottom of the drive core (approximately 1 m [3 ft]) (D BOT). The pollen data are presented as pollen counts (Table 2-4), pollen percentages (Table 2-5), and pollen concentrations (Table 2-6).

Table 2-4. Pollen Counts From Duck Lake Core

Pollen Type[a]	SURF	B MID	D BOT
Deteriorated	35	8	26
Unknown	2	0	0
Abies	1	0	0
Juniperus	42	0	2
Pinus	273	0	5
Picea	1	1	4
Pseudotsuga	2	0	0
Quercus	13	0	0
Ephedra nevad.	4	0	0
Chenopodiaceae-Amar.	14	0	0
Sarcobatus	1	0	0
Artemisia	13	0	25
*Liguliflorae	52	0	0
Ambrosia	15	0	3
Cirsium	2	0	0
Other Compositae	9	0	2
Gramineae	43	2	1
Cruciferae	1	0	0
Polygonum cf. P. calif.	2	0	0
*Populus	1	0	0
*Salix	7	0	1
*Cyperaceae	181	0	1
*Polygonum cf. P. amphib.	4	0	0
*Potamogeton	5	0	0
*Botryococcus	11	0	355
*Fungal spores (undifferentiated)	73	0	0
Tracers added (x 1,000)	90.6	90.6	90.6
Tracers recovered	240	212	284
Volume of sediment used (cm^3)	1	1	1

Note: Samples were analyzed by Owen K. Davis, University of Arizona at Tucson.

(a) Pollen types denoted with "*" are aquatic pollen; the remainder are upland species that are typical for the western United States.

Table 2-5. Pollen Percentages From Duck Lake Core

Pollen Type(a)	SURF	B MID	D BOT
Deteriorated	7.4	72.7	38.2
Unknown	0.4	0	0
Abies	0.2	0	0
Juniperus	8.9	0	2.9
Pinus	57.7	0	7.4
Picea	0.2	9.1	5.9
Pseudotsuga	0.4	0	0
Quercus	2.7	0	0
Ephedra nevad.	0.8	0	0
Chenopodiaceae-*Amar.*	3.0	0	0
Sarcobatus	0.2	0	0
Artemisia	2.7	0	36.8
*Liguliflorae	11.0	0	0
Ambrosia	3.2	0	4.4
Cirsium	0.4	0	0
Other Compositae	1.9	0	2.9
Gramineae	9.1	18.2	1.5
Cruciferae	0.2	0	0
Polygonum cf. *P. calif.*	0.4	0	0
**Populus*	0.2	0	0
**Salix*	1.5	0	1.5
*Cyperaceae	38.3	0	1.5
**Polygonum* cf. *P. amphib.*	0.8	0	0
**Potamogeton*	1.1	0	0
**Botryococcus*	2.3	0	522.1
*Fungal spores (undifferentiated)	15.4	0	0
Tracers added (x 1,000)	90.6	90.6	90.6
Tracers recovered	240	212	284
Volume of sediment used (cm^3)	1	1	1
Concentration(b)	178.6	4.7	21.7
Pollen sum(c)	473	11	68

Note: Samples were analyzed by Owen K. Davis, University of Arizona at Tucson.

(a) Pollen types denoted with "*" are aquatic pollen; the remainder are upland species that are typical for the western United States.

(b) Concentration expressed in grains per cubic centimeter, x 1,000

(c) The pollen sum (divisor for percentages) includes only upland species. Pollen percentages derived for aquatic pollen types represent pollen counts divided by the sum of upland types. This procedure prevents the aquatic pollen types from affecting percentages of upland types through statistical constraint.

Table 2-6. Pollen Concentrations From Duck Lake Core

Pollen Type[(a)]	SURF[(b)]	B-MID[(b)]	D-BOT[(b)]
Deteriorated	13.2	3.4	8.3
Unknown	0.8	0	0
Abies	0.4	0	0
Juniperus	15.9	0	0.6
Pinus	103.1	0	1.6
Picea	0.4	0.4	1.3
Pseudotsuga	0.8	0	0
Quercus	4.9	0	0
Ephedra nevad.	1.5	0	0
Chenopodiaceae-Amar.	5.3	0	0
Sarcobatus	0.4	0	0
Artemisia	4.9	0	8
*Liguliflorae	19.6	0	0
Ambrosia	5.7	0	1
Cirsium	0.8	0	0
Other Compositae	3.4	0	0.6
Gramineae	16.2	0.9	0.3
Cruciferae	0.4	0	0
Polygonum cf. P. calif.	0.8	0	0
*Populus	0.4	0	0
*Salix	2.6	0	0.3
*Cyperaceae	68.4	0	0.3
*Polygonum cf. P. amphib.	1.5	0	0
*Potamogeton	1.9	0	0
*Botryococcus	4.2	0	113.3
*Fungal spores (undifferentiated)	27.6	0	0
Tracers added (x 1,000)	90.6	90.6	90.6
Tracers recovered	240	212	284
Volume of sediment used (cm^3)	1	1	1

Note: Samples were analyzed by Owen K. Davis, University of Arizona at Tucson.

(a) Pollen types denoted with "*" are aquatic pollen; the remainder are upland species that are typical for the western United States.

(b) Concentrations expressed in grains per cubic centimeter, x 1,000.

The pollen percentages in the surface sample are typical for samples taken from modern pine forest in the western United States. Nearly 60 percent of the pollen is pine (Pinus); most of the pine grains are of the ponderosa pine type. Grass (Graminae), juniper (Juniperus), and deteriorated pollen are the only other upland pollen types having over 5 percent concentrations. The importance of the aquatic vegetation in the pollen rain can be seen in the high sedge (Cyperaceae) percentages (38.3 percent), reflecting the presence of sedges growing around the lake today. The concentration of pollen in this sample (178,600 grains/cm^3) is also typical for this type of lake and vegetation type (Davis, 1983).

In contrast to the upper sample, the two lower samples have poor preservation and low pollen concentration. Over 70 percent of the pollen in the middle sample was deteriorated and could not be identified; furthermore, the concentration was only 4,700 grains/cm^3. This poor preservation probably indicates desiccation of the lake sediments in the past (Davis, 1983).

The preservation of the bottom sample was better than that of the middle sample, but the percentages necessitated that interpretations be made with caution. Nearly 40 percent of the grains were too poorly preserved to be identified, and the low concentration of upland species (22,300 grains/cm^3) may indicate that many of the pollen grains have been destroyed. However, the relative percentages of the pollen types in this sample are similar to those found in sediments of late glacial age elsewhere in the Southwest. In particular, the sagebrush (Artemisia) and spruce (Picea) percentages are higher than those in the surface sample. These percentages are typical of spruce parkland found today at higher elevation in the Abajo Mountains (Davis, 1983).

The poor preservation in the lower two samples precludes further examination of this core. However, longer cores from the center of the lake may yield pollen that is better preserved. Although the interpretation of the bottom sample is uncertain, the pollen percentages suggest that sediments of late glacial age are present in Duck Lake. A more complete core from the lake could provide a high-elevation record for comparison with the pollen and macrofossil data derived from pack rat middens at the topographically lower Fishmouth Cave and Allen Canyon Cave sites to the south.

2.4 MALACOLOGY (SNAIL STUDIES)

Fossil snails are not common in Quaternary deposits in the Paradox Basin, but their occurrence has been noted at a few locations, particularly in the Elk Ridge area. Snails, like other organisms, favor specific environmental niches; therefore, the study of fossil mollusks preserved in Quaternary materials might provide indications of the climate, nearby vegetation, and depositional processes that characterized the area at that time. Additionally, age assessments can be made on snail shells by both amino acid and carbon-14 (^{14}C) analyses, or by radiocarbon analysis of organic or carbonaceous material found in deposits in conjunction with the shells.

2.4.1 Previous Studies

Salkin (1975) reported a study of mollusks found in an alluvial sequence exposed in Kane Gulch in the western Elk Ridge area (Figure 2-2). This is the same location where pollen was studied by West (1978) (Section 2.3.1). Salkin's climatic interpretation, based on the snail assemblages present in different stratigraphic units, agreed with his environmental interpretation of the sedimentology of the fluvial deposits. The lower 4 m (13 ft) of the exposure consist of red laminated silt, clay, and fine sand. They contain mollusk assemblages that suggest conditions oscillating between warmer drier intervals, and wetter cooler periods during which some ponding occurred. Above an unconformity marked by a gravel conglomerate at a depth of 1.3 m (4.3 ft), increasingly drier conditions with an associated depletion of vegetative cover were interpreted by Salkin on the basis of the molluscan fauna, and the sand and gravel deposits. Age control was provided by one ^{14}C date of 7,385±80 years BP (Salkin, 1975, WIS-742) on charcoal collected approximately 1 m (3 ft) above the base of the deposits. Subsequently, Woodward-Clyde Consultants (WCC) also collected charcoal from the lowermost units of Salkin's exposure; a ^{14}C date of 8,100±345 years BP (DIC-2064) (Section 4.1.2) substantiated Salkin's initial date. Therefore, the climatic change to increasingly drier conditions, as inferred by Salkin, occurred after approximately 7,400 years BP.

In an associated study, West (1978) analyzed the pollen in Salkin's alluvial sequence (Section 2.3.1) and interpreted the same long-term climatic trends. However, West's detailed examination of the pollen collected from Salkin's climatic zones generally yielded opposite interpretations. This unresolved discrepancy may be the result of poor preservation of pollen in the deposits, or incorrect interpretation of the snail or pollen data.

2.4.2 Current Studies

Snails were collected at seven sites during WCC soil studies in 1981. The snails were not abundant and were generally restricted to specific strata within a depositional sequence of fine-grained deposits. Some of these strata are probably fluvially reworked eolian deposits. Samples were collected from six locations in the Elk Ridge area (Figure 2-2) and from fine-grained deposits in an abandoned meander of the Colorado River near Hite (Figure 1-1; Locality 51) to assess whether paleoclimatic interpretations could be derived from the assemblages. Age control was provided by amino acid analysis of the shells, and by radiocarbon dates derived from charcoal in associated deposits. The samples were sent to the Laboratory of Paleoenvironmental Research, University of Arizona, Tucson, for species identification and interpretation. A total of 6,352 gastropods and pelecypods were identified from the seven sites. The snails were subsequently sent to William Pratt at the Museum of Natural History, University of Nevada at Las Vegas, for his assessment (Pratt, 1985) of the paleoecological significance of the collected assemblages. All of the species can be found in southern Utah or northern Arizona at the present time, and therefore do not represent extinct fauna.

The following ecological assessments made by Pratt are based on the snail assemblages found at individual sites (Tables 2-7 and 2-8), and the environmental conditions favored by contemporary occurrences of individual species.

Table 2-7. List of Identified Mollusks From Seven Sites in Southeastern Utah (Page 1 of 2)

Identified Mollusks (Family Genus species)	51 500,000 +300,000 −200,000 yr BP	63 12,500±150 yr BP	64 5,000±2,000 yr BP	65 24,000±7,000 yr BP	66 19,000±6,000 yr BP	67 9,490±90 yr BP 7,840±700 yr BP	79 >9,000, <30,000 yr BP
	LOCALITY AND AGE						
I. CLASS GASTROPODA							
Terrestrial Snails							
Helicarionidae							
Euconulus fulvus				5		4	
Zonitidae							
Zonitoides arboreus						8	
Limacidae							
Deroceras aenigma			2		23		
Discidae							
Discus cronkhitei				16		50	
Succineidae							
Catinella sp. and/or *Succinea* sp.		50	311	60	113	432	19
Pupillidae							
Pupilla muscorum		3	176	505	454	30	351
Pupilla cf. *P. hebes*				118			
Pupilla sp.				474			
Vertigo ovata		10			36	5	
Vertigo cf. *V. gouldii*						?	
Vertigo cf. *V. binneyana*			36				
Vertigo modesta ingersolli						4	
Vallonidae							
Vallonia cyclophorella			306	632	808	656	109
Vallonia gracilicosta		5				14	

Table 2-7. List of Identified Mollusks From Seven Sites in Southeastern Utah (Page 2 of 2)

Identified Mollusks (Family *Genus species*)	LOCALITY AND AGE						
	51 500,000 $^{+300,000}_{-200,000}$ yr BP	63 12,500±160 yr BP	64 5,000±2,000 yr BP	65 24,900±7,000 yr BP	66 19,000±6,000 yr BP	67 9,490±90 yr BP 7,840±700 yr BP	79 ≥29,000, <30,000 yr BP
Freshwater Snails							
Lymnaeidae							
Stagnicola pilsbryi						1	
Fossaria parva		27	23	16	66	103	
Fossaria obrussa						1	
Physidae							
Physella virgata	213						
2. CLASS BIVALVIA							
Sphaeriidae							
Pisidium casertanum					3	3	
Pisidium compressum	42						
Pisidium ventricosum	2						
Total shells	257	95	854	1,846	1,503	1,318	479
Total taxa	3	5	6	8	7	14	3

Note: See Figures 1-1 and 2-2 for locations of sampling sites.

Table 2-8. Percentage Representation of Mollusk Species From Sites in Southeastern Utah (Page 1 of 2)

Identified Mollusks (Family Genus species)	51 500,000 +300,000 -200,000 yr BP	63 12,500±160 yr BP	64 5,000±2,000 yr BP	65 24,000±7,000 yr BP	66 19,000±6,000 yr BP	67 9,490±50 yr BP 7,840±700 yr BP	79 29,000, ≤30,000 yr BP
1. CLASS GASTROPODA							
Terrestrial Snails							
Helicarionidae							
Euconulus fulvus				<1		<1	
Zonitidae							
Zonitoides arboreus						<1	
Limacidae							
Deroceras aenigma			<1		1		
Discidae							
Discus cronkhitei				<1		4	
Succineidae							
Catinella sp. and/or *Succinea* sp.		53	36	4	7	33	4
Pupillidae							
Pupilla muscorum		3	20	27	30	2	73
Pupilla cf. *P. hebes*				6			
Pupilla sp.				26			
Vertigo ovata		10			2	<1	
Vertigo cf. *V. gouldii*						<1	
Vertigo cf. *V. binneyana*			4				
Vertigo modesta ingersolli						<1	
Vallonidae							
Vallonia cyclophorella			36	34	54	50	23
Vallonia gracilicosta		5				1	

Table 2-8. Percentage Representation of Mollusk Species from Sites in Southeastern Utah (Page 2 of 2)

Identified Mollusks (Family Genus species)	LOCALITY AND AGE						
	51 500,000$^{+300,000}_{-200,000}$ yr BP	63 12,500±160 yr BP	64 5,000±2,000 yr BP	65 24,000±7,000 yr BP	66 19,000±6,000 yr BP	67 9,490±90 yr BP 7,840±700 yr BP	79 ≥29,000, <30,000 yr BP
Freshwater Snails							
Lymnaeidae							
Stagnicola pilsbryi						<1	
Fossaria parva		28	3	<1	4	8	
Fossaria obrussa						<1	
Physidae							
Physella virgata	83						
2. CLASS BIVALVIA							
Sphaeriidae							
Pisidium casertanum					<1	<1	
Pisidium compressum	16						
Pisidium ventricosum	1						
Total shells	257	95	854	1,846	1,503	1,318	479
Total taxa	3	5	6	8	7	14	3

Note: See Figures 1-1 and 2-2 for locations of sampling sites.

At all localities, with the exception of Locality 51, the snails were collected from arroyo exposures along ephemeral streams having water flow during the spring and fall months, or after intense summer rainfall.

1. Locality 51: The paleoenvironment at Locality 51 on the Colorado River was different from that at the other sites, as indicated by both the geologic setting and the fauna. The quiet-water deposits at the site may have accumulated behind a landslide that dammed an abandoned meander of the Colorado River. Amino-acid data (Section 4.1.4) and the topographic position of the meander above present stream level indicate that mollusk[illegible]nd in this locality are significantly older than those found [illegible] other sites (Tables 2-7 and 2-8). The three species collected from this locality are all characteristic of lakes or permanent streams. The absence of any land snails suggests that the fauna is in situ rather than of drift origin. The faunal analysis therefore substantiates the sedimentology.

2. Locality 63: The snail samples were collected from a clay-rich unit within sand and gravel deposits that are overlain by eolian deposits. This is an in situ assemblage that is indicative of marshy areas. A radiocarbon date derived from shell material is 12,500±2,000 years BP.

3. Locality 64: The sample site is a bank exposure in Comb Wash. An amino acid date derived from analysis of the snail shells provided a date of 5,000±2,000 years BP. The snail assemblage collected at Locality 64 is probably a drift assemblage that has not been transported a great distance. A wet or marshy area was present not far upstream; however, the marshes were not extensive. Species characteristic of permanent water are lacking, which suggests that the stream was not perennial at this location. Species characteristic of mesic montane conifer forest are also not found.

4. Locality 65: These snail samples were also collected from an arroyo bank exposed in Dry Wash. An amino acid date derived for the snail shells is 24,000±7,000 years BP. The assemblage represents a drift deposit from marshy areas upstream.

5. Locality 66: This assemblage was also collected from Dry Wash, and was found in fine-grained alluvium overlain by eolian deposits. An amino acid date of 19,000±6,000 years BP may be too young, because the snails were collected from beneath a well-developed calcic soil that may represent more than 100,000 years of soil development. The snails are indicative of an intermittent stream, with nearby marshy areas of limited extent or at some distance upstream.

6. Locality 67: The snails were collected in a carbon-rich horizon exposed in a cut bank of Dry Wash, adjacent to a perenially marshy area. Duplicate radiocarbon dates obtained from the carbon-rich soil are 7,840±700 and 9,490±90 years BP. Amino acid analyses of the snail shell material suggest that the older ^{14}C date may be more accurate. This snail assemblage also suggests the presence of marshy areas at no great distance from the site. These are

attributed to the reduction of an intermittent stream to a series of marshy areas without flow during the dry season.

7. Locality 79: The snail assemblage was collected from finely laminated to massive sandy alluvium, which is interpreted as representing occasionally ponded deposits. An amino acid date of between 9,000 and 14,000 years BP derived for these deposits is thought to be too young; they are more likely on the order of 50,000 to 100,000 years old (Section 4.2.3.1.6). The faunal assemblage is a drift deposit, and does not contain environmentally informative species.

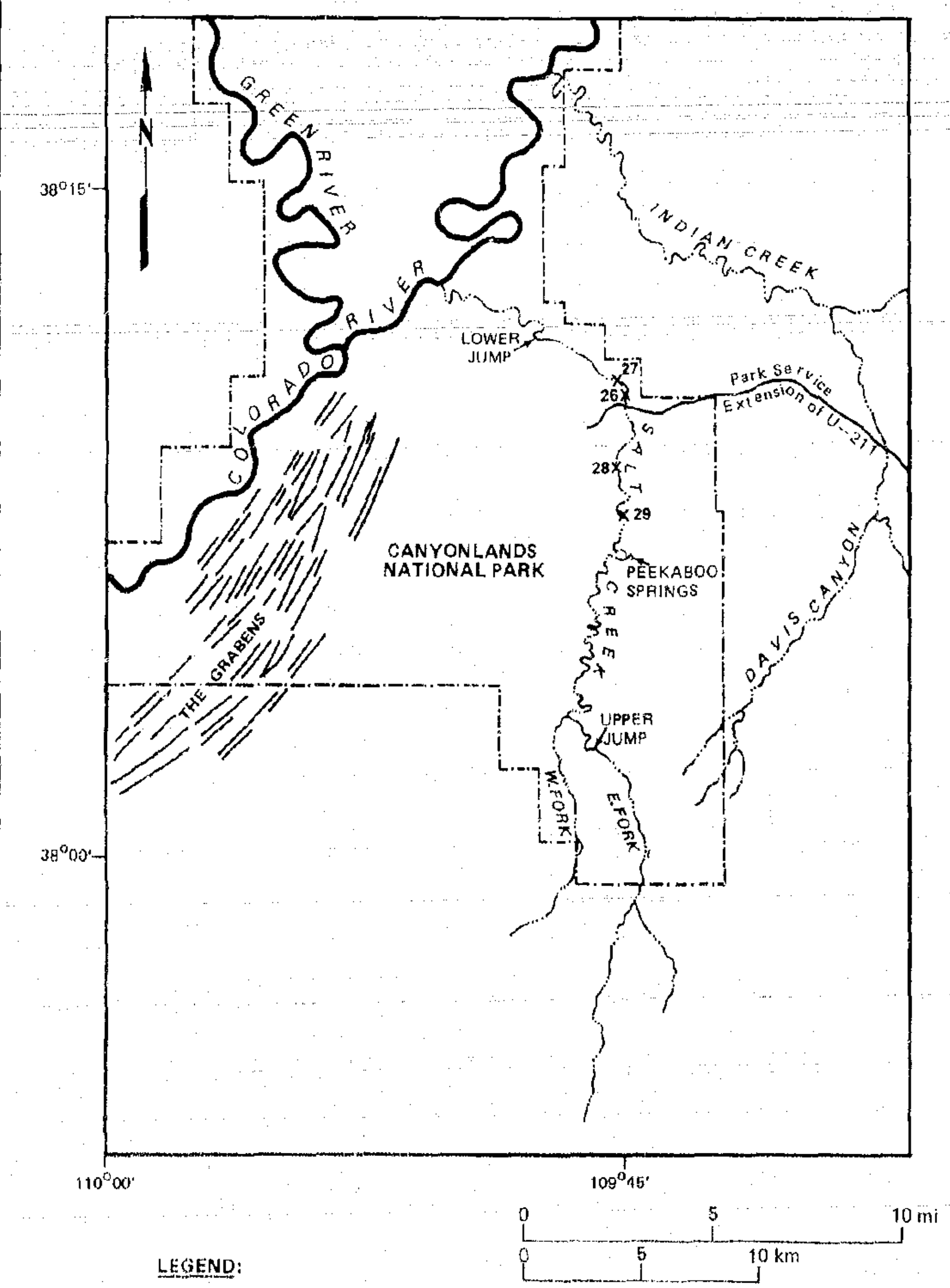
Although the combination of species in the snail assemblages that were sampled varied, the paleoecological interpretations for the Elk Ridge area are indicative of relatively dry conditions in which streams were intermittent and reduced to marshy areas without connecting flow during the dry season. The limited land snail data suggest a rather xeric conifer forest with a sparse ground layer such as that presently found in ranges of the Great Basin, rather than the lusher forest of Utah and Arizona ranges. These interpretations did not vary much between sites, despite the chronologic differences, suggesting that climatic variations during late Pleistocene time were not of a magnitude that could be readily discernible at this level of study. The age control provided for many of the sites has been assessed as not accurately indicative of the age of the deposit. With better age control, it may be possible to make some significant interpretations of paleoclimatic change from fossil mollusk assemblages.

2.5 HOLOCENE CHRONOSTRATIGRAPHY, SALT CREEK

Examination of Holocene alluvial fill deposits in the vicinity of Gibson Dome was initiated in 1982 to assess whether distinct Holocene stratigraphic units can be identified and used to define the timing of climatic changes that have occurred in the last 10,000 years, and to predict the return intervals of major infrequent floods. If recognizable lithostratigraphic units are present, the nature of the deposits can indicate fluvial responses to past climatic changes. These data can be used to predict the magnitude and character of similar geomorphic responses to comparable future climatic changes that may occur during the lifetime of a high-level nuclear waste repository.

Because of land access restrictions imposed on Paradox Basin studies in 1982 regarding other parts of the Paradox Basin, Salt Creek, a northward flowing ephemeral stream along the eastern border of Canyonlands National Park, was chosen for the initial Holocene stratigraphy studies. Four exposures over a 6.5-km (4-mi) stretch of Salt Creek between Peekaboo Springs and the Lower Jump (Figure 2-5) were examined. During this preliminary study, the emphasis was on identification of units that might be correlative, or indicative of climatic changes.

Several charcoal samples were collected from morphologically similar geologic units mapped in the field to assess whether they are time equivalent. A total of 19 ^{14}C dates was obtained from these exposures (Figure 2-6 and Table 2-9). Because the samples were of small size, most were sent to the Radiocarbon Laboratory at Washington State University, Pullman, Washington,



LEGEND:

X28 Locality referred to in text, in Tables 1-1 and 2-9, and on Figure 2-6

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MAP OF SALT CREEK AND VICINITY

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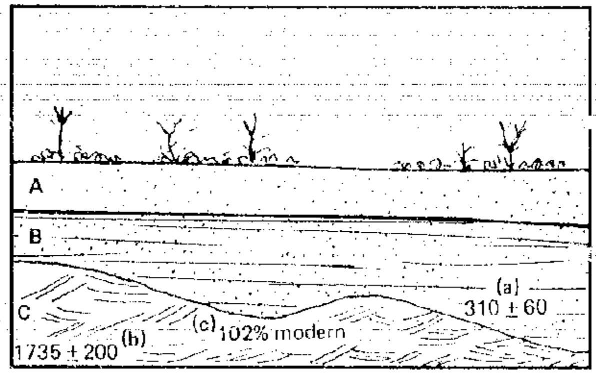
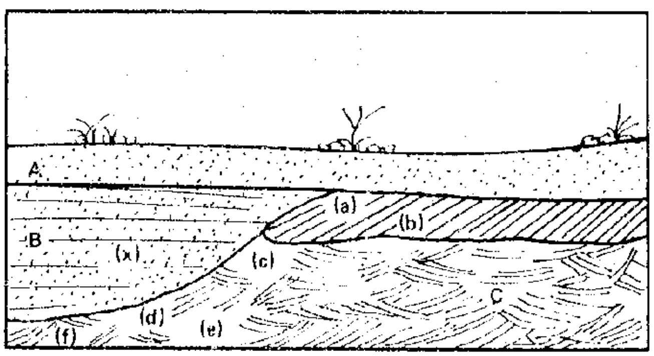
LOCALITY 26



LEGEND:

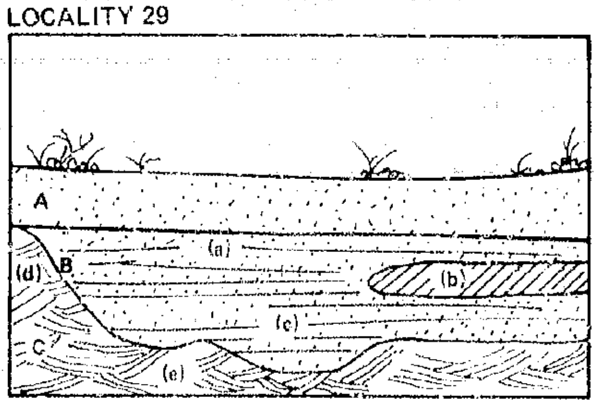
- EOLIAN SAND
- RHYTHMICALLY BEDDED SAND AND CLAYEY-SILT
- CROSS-BEDDED SAND
- MUDFLOW DEPOSIT
- B — DEPOSITIONAL UNIT
- (a) — ^{14}C SAMPLE SITE:
- 310 ± 60 — DERIVED DATE (YEARS BP)

LOCALITY 27



B
(x) 3360 ± 190
C
(a) 2080 ± 200
(b) 2920 ± 220
(c) 2530 ± 210
(d) 1460 ± 250
(e) 2500 ± 210
(f) 1790 ± 70
1710 ± 260

LOCALITY 29



B
(a) 580 ± 150
1690 ± 230
2385 ± 55
(b) 2430 ± 70
(c) 120% modern
C
(d) 4830 ± 640
(e) 1640 ± 210

SEE TABLE 2–9 FOR ADDITIONAL DATA REGARDING RADIOCARBON DATES

SCHEMATIC DIAGRAMS ARE NOT DRAWN TO SCALE

LOCATIONS OF SAMPLING SITES ARE SHOWN ON FIGURE 2–5.

STRATIGRAPHIC SETTING OF RADIOCARBON DATES, SALT CREEK
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Figure 2-6

Table 2-9. Radiocarbon Dates From Salt Creek Holocene Strata

Proposed Unit	Locality[a]		Carbon-14 Dates (yr BP)[b]	Laboratory Sample No.[c]	Weight Used (g)	Comment
A. Eolian Sand (Uppermost)						No dates obtained.
B. Rhythmically bedded unit (Middle)	26	(a)	310 ± 60	WSU-2776	6	Plant matter (flood debris)
	27	(x)	3,360 ± 190	WSU-2805	0.479	Charcoal
	28		4,510 ± 600	WSU-2777	0.215	Charcoal
	29	(a)	580 ± 150	DIC-2642		Charcoal collected from burn
			1,690 ± 230	BETA-6220		horizon at top of Unit B;
			2,385 ± 55	WSU-2755	43.7	sample split in triplicate
		(b)	2,430 ± 70	WSU-2801	5.0	Charcoal
		(c)	120% modern	WSU-2802	23.457	Charcoal and sand; included 0.741 g of separated charcoal
C. Cross-Bedded Fluvial Sand (Lowermost)	26	(b)	1,735 ± 200	WSU-2798	0.974	Charcoal
		(c)	102% modern	WSU-2754	3.0	Charcoal with sand; some
			No carbon	DIC		charred bone; sample split
			No carbon	BETA		for triplicate dating
	27	(a)	2,080 ± 200	WSU-2774	1.5	Charcoal with sand; date derived using barium hydroxide process; sample (a) was collected from uppermost mudflow that may represent transition to Unit B.
		(b)	2,920 ± 220	WSU-2808	0.909	Charcoal
		(c)	2,530 ± 210	WSU-2807	1.3	Charcoal
		(d)	1,460 ± 250	WSU-2804	2.157	Charcoal and sand
		(e)	2,500 ± 210	WSU-2806	8.83	Charcoal and sand; included 0.782 g of separated charcoal
		(f)	1,790 ± 70	WSU-2810	2.913	Root sample split for
			1,710 ± 260	WSU-2809	2.155	duplicate dating
	29	(d)	4,830 ± 640	WSU-2800	3.787	Charcoal with sand
		(e)	1,640 ± 210	WSU-2799	0.831	Charcoal

(a) See Figures 1-1 and 2-5, and Table 1-1.
(b) Stratigraphic settings of samples are shown on Figure 2-6.
BP = Years before 1950 A.D. "Modern" is post-1950.
(c) WSU - Washington State University, Pullman, Washington
DIC - Dicarb Radioisotope Company, Norman, Oklahoma
BETA - Beta Analytic, Incorporated, Coral Gables, Florida.

which has facilities to handle small samples. Two samples were sufficiently large to split; the sample splits were sent to Beta Analytic, Inc., Coral Gables, Florida. A third split of one of the samples was sent to Dicarb Radioisotope Company, Norman, Oklahoma.

2.5.1 Geomorphic Setting

For most of its length south of the paved Park Service extension of Highway U-211 (Figure 2-5), Salt Creek flows northward through narrow, well-developed, incised meanders in the Cedar Mesa Sandstone. In the vicinity of the highway, however, less resistant units crop out and the stream valley is broader. Farther downstream, the stream has eroded through a thin resistant limestone bed at the Lower Jump (Figure 2-5), and has carved a narrow bedrock canyon that extends downstream to the Colorado River. Upstream of the Lower Jump, fine-grained Holocene sediments that form the floor of a 30- to 300-m (100- to 1,000-ft) -wide valley are now being removed by the gullying of Salt Creek. However, one tributary, the West Fork of Salt Creek, appears to be aggrading directly upstream of its juncture with Salt Creek.

Eolian processes have also been active in the area during Holocene times, as evidenced by the dune forms observed on the leeward side of bedrock knobs and in tributary box canyons. Modern northeast-trending dunes occur east of Salt Creek, approximately 1 km (0.5 mi) north of the highway.

2.5.2 Salt Creek Deposits

Preliminary observations suggest that at least three units, with different depositional characteristics, comprise the exposed Holocene fill in Salt Creek. Additional study is needed to assess whether they are chronologically separate and of regional extent.

The lowermost unit recognized, Unit C, is a cross-bedded, clean, yellow-buff sand. Small pebbly layers are locally present, and small gastropods are relatively abundant. Prominent reddening observed at the upper contact of this unit may be pedogenic, but probably reflects ground-water alteration when the unit occupied the floor of younger channels cut into it. At the southernmost locality, Locality 29 (Figure 2-7), the upper half of a 7-m (23-ft) -high exposure of this unit contains layers of mudstone 10 to 15 cm (4 to 6 in) thick. A weakly developed cambic soil is present. This upper portion may represent a transition zone between the lower and middle units. A ^{14}C date obtained from the upper strata at Locality 29 provided the oldest date (4,830±640 years BP [WSU-2800]) derived from this unit. The other nine ^{14}C dates from Unit C, including a sample stratigraphically lower than the 4,830 years BP date of Locality 29, range between 2,920±220 and 1,460±250 years BP (Figure 2-6; Table 2-9).

The middle Salt Creek unit (Unit B) consists of rhythmically bedded, fine-grained reddish layers (Figure 2-7). The beds consist of thin, organic-rich, clayey silt layers, and thicker fine- to medium-grained cross-bedded sand beds. Massive, poorly sorted beds, up to 2 m (6 ft) thick, also comprise the middle unit, and probably originated as mudflows. Grain sizes range from silt to coarse sand, and small pieces of charcoal and other organic debris are

Holocene fill exposed at Locality 29, Salt Creek. The well sorted, sandy basal unit (C) is cut by a channel filled with rhythmically bedded sand and clayey silt (B). Eolian sand (A) caps the deposit. Sites where three of the samples were collected for ^{14}C dating are shown in parentheses (see Table 2-9).

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HOLOCENE DEPOSITS, LOCALITY 29, SALT CREEK	
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commonly scattered throughout the mudflow deposits. A few other cut-and-fill structures were observed in Unit B. The seven ^{14}C dates derived for samples collected in this unit range from 4,510±600 to 310±60 years BP (Figure 2-6 and Table 2-9).

All exposures examined are capped by Unit A, a massive, medium- to coarse-grained sandy unit, which is tan-red in color and is interpreted to be eolian in origin. No carbonaceous material was found in this unit for radiocarbon age determinations.

2.5.3 Geologic Interpretations

The distinct variations in the depositional character of the Holocene deposits exposed in Salt Creek suggest that environmental conditions have, at least locally, changed over the time period represented in the exposures. However, these changes were not of the same magnitude of change that occurred at the end of the Pleistocene (approximately 10,000 years BP). The cross-bedded sand of Unit C is indicative of a sandbed stream having sufficient velocity to develop dune forms on its bed (Leopold et al., 1964). Quantitative measurements that could potentially provide estimates of flow depths and velocity were not obtained from the cross-bedding during this preliminary study. At Locality 29, the sandy deposits graded upward to mudstone layers, suggesting a transition to conditions leading to over-bank, quiet deposition.

The middle unit, Unit B, consists predominantly of layers that suggest a cyclic depositional environment varying between over-bank, quiet-water conditions (the mudstone layers) to stream channel flow (the sandy horizons). However, channel velocities were not sufficient to produce bed dune forms comparable to those developed in the underlying unit (Unit C). Occasionally, mudflows moved down the channel, resulting in deposits as much as 2 m (6 ft) thick.

The uppermost unit, Unit A, appears to be eolian in origin. Fluvial reworking of these deposits was probably minimal because of the lack of fluvial structures in the massive deposits. At Locality 27, the streambank exposure is a cross section of a northeast-trending dune that is a part of the dune field north of the stream.

The sedimentological character of the Holocene deposits exposed by gullying of Salt Creek suggests that there may have been a sustained flow in Salt Creek while the lower part of Unit C was being deposited. Either a significant amount of silt- and clay-sized particles was not being carried by the stream at this time, or the velocity was sufficiently swift to carry these particle sizes farther downstream.

The transition to more episodic flow conditions indicated by Unit B may be represented by the upper horizons of Unit C. During this time, higher flows cut channels in Unit C and moved mudflows down the channels. The mud and silt horizons may represent the stripping of surface soil horizons from hillslopes destabilized by a shift to drier climate conditions punctuated by more intense, brief rainfall events. Alternatively, the stripping could be caused by infrequent major storms.

No evidence of channel cutting was observed in the time interval represented between the deposition of Units A and B. The interpreted eolian origin of Unit A suggests that drier conditions prevailed, enabling the transport of the windblown, fine-grained material.

Although the Holocene fluvial deposits suggest definite changes in flow regimes, significant leaching of pre-Holocene calcic soils by an increase in rainfall during the Holocene is not apparent. Therefore, climatic conditions must have remained arid to semiarid throughout this period, an interpretation that is supported by vegetational analyses of fossil pack rat middens (Section 2.2).

2.5.4 Derived Age Data

Sequential environmental changes have been inferred from the sedimentological character of Holocene deposits in Salt Creek. Age dates of the deposits are essential for dating these changes, assessing if these changes correlate with paleoclimatic interpretations derived by other means, and for verifying that the depositional units are not time-transgressive facies variations. A total of 10 radiocarbon dates was derived from the lowermost deposits that herein have been collectively referred to as Unit C. These dates range from 4,830±640 years BP to 102 percent modern (Figure 2-6; Table 2-9), and 80 percent of the dates are between 2,920 and 1,460 years BP. Dates from deposits referenced as the Middle Unit, Unit B, exhibit a wide scatter between 4,510±600 and 310±60 years BP (Table 2-9). The dates do not provide an evident chronologic separation of Units B and C of the Salt Creek deposits.

At Locality 26, only one date each was derived from Units B and C (Figure 2-6). A date of 310±60 years BP (WSU-2776; Table 2-9) was obtained from matted flood debris, consisting of plant material and pack rat fecal pellets from Unit B. This should be an accurate reflection of the age of the deposit because it is unlikely that the plant debris would have been reworked from another deposit. Also the sample size was large, thus reducing analytical error. The underlying unit (Unit C) yielded a date of 1,735±200 years BP (WSU-2798) from detrital charcoal (Table 2-9). The two dates are stratigraphically reasonable, although the charcoal may have been reworked from an older source.

At Locality 27, the date derived from detrital charcoal in the middle stratigraphic unit, Unit B, is older than all the dates derived from the underlying unit, Unit C (Figure 2-6; Table 2-9). It is therefore likely that the charcoal found in Unit B was reworked from older deposits. Dates derived for the six sampling sites within Unit C are also stratigraphically inverted, with the oldest dates derived from the mudflow in the upper part of the unit. The stratigraphically lowest sample (f, Figure 2-6; Table 2-9) was interpreted to be a root by the analyzing laboratory; the reproducibility of the derived dates for the sample indicates they are good. Therefore, the sample date (1,750 years BP [average]) probably represents the time when a plant was growing in the deposit of interest. The other young date (1,460±250 years BP [WSU-2804]) at the base of the unit may also be the remains of a root.

Only one date was derived at Locality 28 (Table 2-9). Detrital charcoal collected from deposits having sedimentological characteristics of Unit B provided a date of 4,510±600 years BP (WSU-2777). This sample was of very small size (0.215 g) (Table 2-9), and the derived date is older than others from this unit. Therefore, it may not accurately reflect the age of the deposits, either because of analytical error introduced by an inadequate amount of the sample, or because the collected charcoal was reworked from an older deposit.

Dates were received for four sampling sites at Locality 29 (Figure 2-6; Table 2-9). Triplicate dates were run on samples collected from a burn horizon near the top of Unit B to compare reproducibility among three laboratories. Although samples sent to the laboratories were of small but adequate quantities, the resulting dates, 580±150, 1,690±230, and 2,385+55 years BP (Table 2-9), were nonreproducible. All are stratigraphically reasonable for the unit and postdate the 2,430±70 years BP (WSU-2801) date for an underlying mudflow. The two dates derived from charcoal collected from Unit C are stratigraphically inverted. The older date of 4,830±640 years BP (WSU-2800) may represent the age of the unit; or the collected sample may have been reworked from an older deposit, or may be the center wood of a recently deceased, old tree. The younger date of 1,640±210 years BP (WSU-2799) was from a small sample and may have been a charred root of a plant that postdated deposition of the unit.

2.5.5 Discussion

The sedimentological character of the Holocene fill in Salt Creek streambank exposures suggests that three distinct depositional units occur within the portion of the channel examined. These consist of a lowermost sandy, cross-bedded unit (Unit C); a middle unit consisting of rhythmically bedded sandy and silty-clay layers (Unit B); and an uppermost eolian deposit (Unit A).

However, radiocarbon dates acquired from Units B and C do not define two chronologically distinct units. Many of the dates appear to give inaccurate ages for the deposits, based on stratigraphic relationships. One possible explanation is that the collected charcoal was reworked from older deposits, and therefore provides a minimum limit on the age of the unit rather than an accurate assessment of time of deposition. Error may also have been introduced into the age calculations by the small size of many of the analyzed samples.

Taking all of the aforementioned factors into consideration, the following qualifying statements can be made about the Salt Creek Holocene fill units. The age of the exposed part of the lowermost unit (Unit C) is probably bracketed between 4,830±640 and 1,710±260 years BP. The capping mudflow deposit at Locality 27 was deposited, at a maximum, 2,920±220 years BP. The maximum age for the middle unit (Unit B), which was deposited after the mudflow cap of Unit C filled the channel at Locality 27, is 3,360±190 years BP, and is more likely 2,080±200 years BP. The date of 310±60 years BP derived from near the top of this unit at Locality 26 may be the most accurate date derived from all the Salt Creek samples because the sample was of adequate size and could not have been reworked from older deposits. However, only the youngest (580±150 years BP) of the discordant triplicate dates from near the top of the unit at Locality 29 is supportive of such a young date for the unit. Unit A postdates Unit B in age and is probably still accumulating through eolian depositional processes.

The results of this preliminary effort to correlate Holocene deposits in Salt Creek indicate the need for (1) additional age control through either radiocarbon or TL dating, (2) careful collection of samples to be dated, and (3) the tracing of the lateral extent of deposits in streambank exposures. More extensive age control may also indicate, however, that the deposits are not chronologically distinct units, and therefore not climatically controlled.

Elsewhere, recent studies of ephemeral streams in the Southwest have emphasized the concept of sediment storage in the drainage basin, and the episodic transport of sediment out of the basin during a series of cut-and-fill cycles (Patton and Schumm, 1975; Patton and Boison, 1986; Boison and Patton, 1985). The underlying premise of this concept is that erosion or deposition within a stream channel is in response to threshold conditions of instability, and is not due to climatic controls. Both processes may be occurring concurrently in localized areas within the same drainage basin. These concepts have developed from 22 years of measurements in specific streams (Patton and Schumm, 1975) and from interpretations of Holocene terrace deposits in Harris Wash in southcentral Utah (Patton and Boison, 1986). In the latter study, three distinct sedimentary facies (a thick-bedded sand facies, a ripple-stratified red-and-tan sand facies, and a thin-bedded mud facies) were recognized throughout the wash, but not in any preferred sequence.

In Salt Wash, the exposures that have been studied exhibit a preferred depositional sequence. Evidence of multiple cut-and-fill events is not plentiful in the exposures examined, but can be seen in exposures on other stream courses in the area. Therefore, it is likely that Salt Creek is transporting sediment through the system in a manner similar to that described by Patton and Schumm (1975) and Patton and Boison (1986). However, this cyclic process appears to be superimposed on larger scale changes that are sufficiently significant to uniformly alter the character of streambed deposits throughout the length of the channel that was studied. These broader scale changes are presently assessed to be climatically controlled. Additional work should include the study of the upstream segment of Salt Creek, and of Holocene fill abundantly exposed in other gullied drainages throughout the area. This would provide an opportunity to assess the regional extent of the three stratigraphic units defined to date, and their chronologic equivalency.

2.6 SUMMARY

A number of biostratigraphic and geologic methods were used in a preliminary assessment of the paleoclimatic changes that have occurred in southeast Utah since latest Pleistocene time. Based on results of preliminary studies, macrofossils collected from pack rat middens most definitely bracket the timing of climate changes at the end of Pleistocene time. This change is also recorded in pollen collected from lake sediments. Refinement of the pollen data could enhance scenarios developed from pack rat data. Snail assemblages and Holocene stratigraphic units examined to date, however, lack sufficient age control for establishing useful paleoclimatic data.

Regional data indicate that the major change from a cool late-Pleistocene climate to conditions that resemble the present-day environment occurred approximately 11,000 to 8,000 years BP. South of the potentially acceptable repository sites at Davis and Lavender Canyons, on the southern flanks of the Abajo Mountains, data collected during this study indicate that vegetation responded to the climatic change approximately 10,000 years BP at a 1,585-m (5,200-ft) elevation, and between 10,000 and 7,200 years BP at a 2,195-m (7,200-ft) elevation. The data are based on macrofossils preserved in pack rat middens examined during the Paradox Basin studies. This change is also recorded in pollen preserved in bottom deposits of Duck Lake in the Abajo Mountains, as shown by evidence collected during this study.

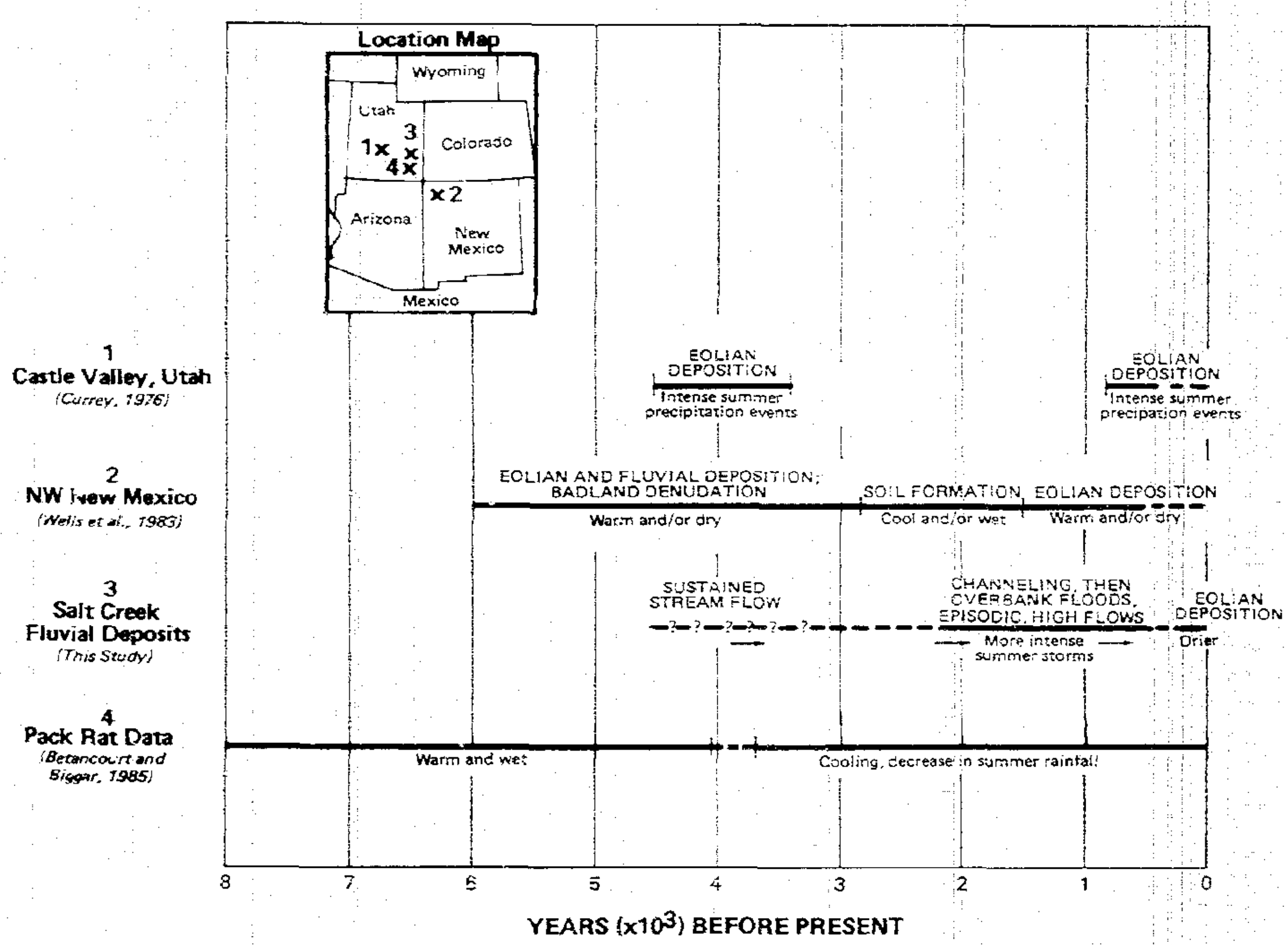
During Holocene time, more subtle global climatic fluctuations have occurred. The paleobiologic record varies as to the nature of these changes. At some locations, such as lowlands in California and southcentral Colorado (Baker, 1983), only a continuous warming trend is observed. Elsewhere, the middle Holocene (7,000 or 8,000 to 4,000 or 5,000 years BP) is marked as a warmer interval than the preceding or successive periods (Baker, 1983). In some areas, such as the northern Great Basin, conditions appear to have been warm and dry (Antevs, 1955). In the southwestern States, they were probably warm and wet due to the enhancement of the monsoonal effect (Martin, 1963; Baker, 1983). Holocene glaciation in western mountain ranges appears to have occurred in a nonsynchronous fashion (Burke and Birkeland, 1983).

Chronologic control on Holocene climatic changes in the study area presently consists of interpretations based on macrofossils found in pack rat middens south of the Abajo Mountains, on sedimentological changes observed in Holocene deposits, and on studies reported in the literature. The pack rat data suggest that conditions were warm and wet between 8,000 and 4,000 years BP. A cooling trend and a decrease in summer rainfall appear to have developed after 4,000 years BP. Fluvial deposits in Salt Creek drainage, on the eastern edge of Canyonlands National Park, suggest that runoff was sufficient to develop a sandbed stream with dune forms on the bed between 4,800 and 2,100 years BP. Flow conditions gradually changed around 2,100 years BP, resulting in channeling of the older sandy deposits, occasional mudflows, and over-bank, quiet-water deposits. These conditions may have been due to intense storms and may have continued up to as recently as 500 to 300 years BP. Since then, eolian activity appears to have increased. The present gullying probably began in the late 1800s.

In northwestern New Mexico, Wells et al. (1983) associated eolian deposition, badland denudation, and fluvial deposition with a warm and/or dry period that occurred between 6,000 and 2,800 years BP. A cool and/or wet period between 2,800 and 1,500 years BP facilitated paleosol formation and stabilization of eolian source material. Another warm and/or dry trend that began around 1,500 years BP has renewed alluvial and eolian depositional processes. In Castle Valley, north of the San Rafael Swell in central Utah, Currey (1976) related eolian depositional periods that occurred between 4,500 and 3,390 years BP and from 1,790 years BP to the early 1900s to a reduction in winter precipitation, intensified summer convective storms, and relatively low soil moisture.

Figure 2-8 is a composite of these climate interpretations. The data span a 450-km (280-mi) -long northwest transect, and represent an area that is transitional between two air mass boundaries. Areas to the south are subject to late summer rainfall derived from moist maritime air from the Gulf of Mexico. The northern part, however, is more influenced by continental airflow from the northwest. Despite these differences, active eolian periods are coincident, though of different duration, across the area.

The climatic interpretations derived from the Salt Creek deposits do not closely parallel the others shown in Figure 2-8. However, with refined age control on the Holocene deposits, the Holocene paleoclimatic trends recorded by other studies may also be reflected in the fluvial depositional record. Alternatively, interpretations of fluvial/deposition conditions and controls may change as the deposits are examined in more detail and other drainages in the area are studied. Unfortunately, the early and middle Holocene stratigraphic record has probably been eroded from narrow stream channels. Such erosion characterizes many of the streams in the Canyonlands area. At present, however, the fluvial record in Salt Creek appears to be responding to an outside forcing factor(s) that is affecting the whole drainage basin. Most likely, this factor is either directly or indirectly related to climatic change.



MIDDLE TO LATE HOLOCENE CLIMATIC CHANGES IN SOUTHEASTERN UTAH AND NORTHWESTERN NEW MEXICO

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Figure 2-8

LOG 2260
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3.0 QUATERNARY STUDIES IN THE NEEDLES FAULT ZONE

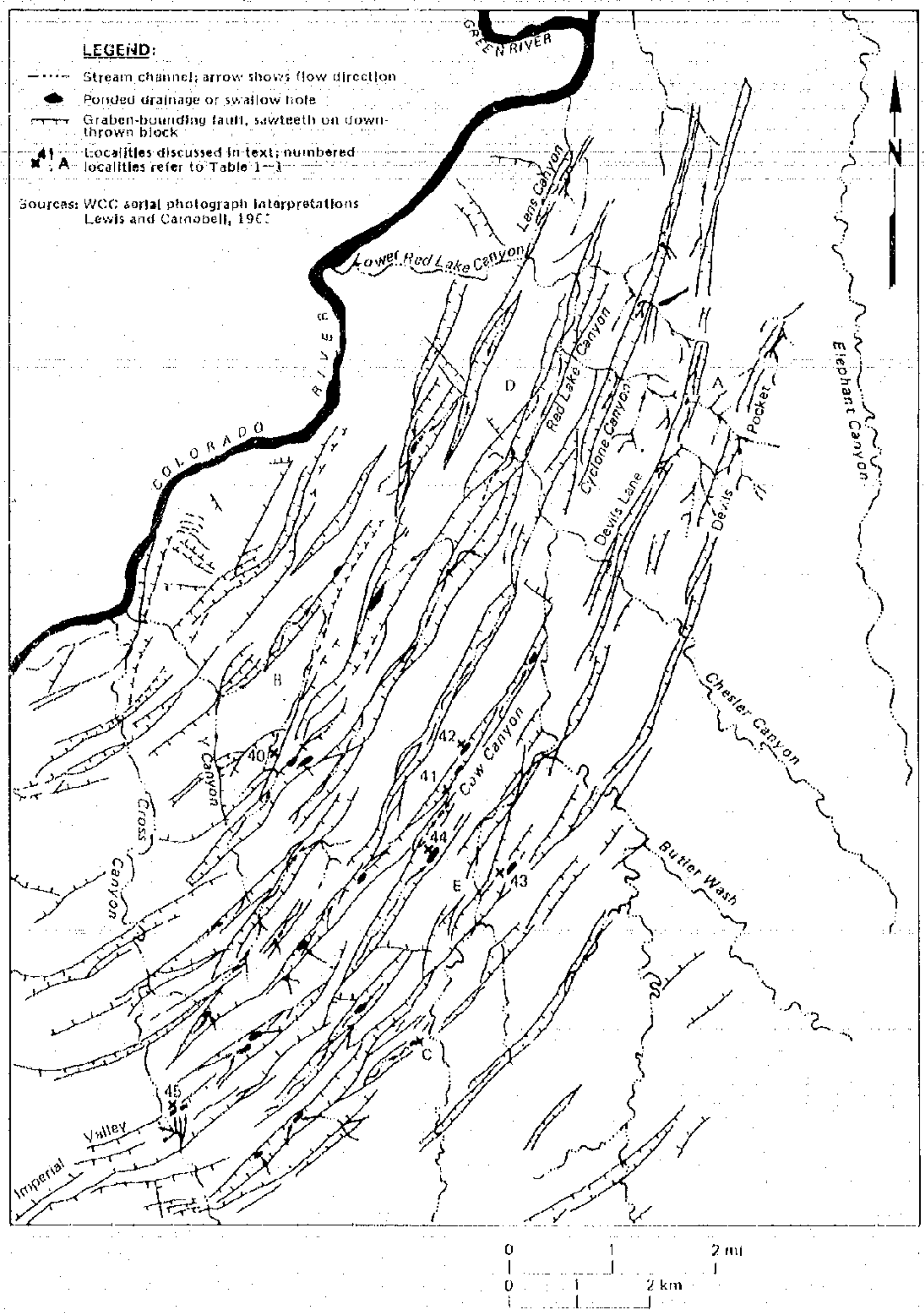
The Needles Fault zone of the Paradox Basin occupies an arcuate zone approximately 27 km (17 mi) long and 14 km (9 mi) wide along the eastern side of the Colorado River immediately below its confluence with the Green River (Figure 3-1). The fault zone consists of a system of northeast-trending extensional valleys (grabens) bounded by normal faults (Figure 3-2). Individual faults generally exhibit vertical displacements that range from a meter (a few feet) to about 30 m (100 ft); however, near Cataract Canyon, up to 100 m (300 ft) of displacement has been reported (Lewis and Campbell, 1965, p. 3). Subsequently, the graben valleys have partially filled with alluvium, colluvium, and eolian deposits.

Most theories on the origin of the Needles Fault zone emphasize gravity tectonics as the cause. Baker (1933), McGill and Stromquist (1974), and Stromquist (1976) propose that canyon cutting along the Colorado River during Quaternary time reduced the overburden above the evaporite sequence of the Paradox Formation. This unloading allowed the viscous evaporite material to flow down the gentle westerly dip of the Monument Upwarp, and resulted in the formation of the Meander anticline along the Colorado River. The grabens formed by extension as strata overlying the salt strata pulled apart along existing joints. Huntoon (1982) does not believe that salt flowage is required for graben formation. He theorizes that the incision of the Colorado River formed a free vertical face or surface, and downdip westward sliding formed the graben features. Hite (1982) credits salt dissolution in the Paradox Formation with collapse of the overlying strata. All of these mechanisms may operate to different degrees, depending on distance from the river, amount of surface water that reaches the evaporite horizon(s), and the preexisting joint system.

Understanding the age, rate, and mechanisms of graben formation is important to repository siting because of the proximity of the Needles Fault zone to the Davis and Lavender Canyon sites. Hence, a preliminary study was undertaken to assess whether Quaternary deposits in the grabens could yield information on the age and rate of graben development. To address this question, photogeologic interpretations, reconnaissance mapping, and sampling of the deposits were conducted during a 2-week period in 1982.

3.1 DRAINAGE ANOMALIES

Examination of aerial photographs revealed that many small drainages in the Needles Fault zone have been disrupted by graben formation. For example, westward-flowing tributaries to Lower Red Lake Canyon, in the northern portion of the Needles Fault zone, have been beheaded by the downdropping of the Devils Lane graben across their channels (Figure 3-3, Locality A; Figure 3-4A). These streams now drain into closed depressions within Devils Lane (Figure 3-4B). In many of the graben valleys that are closed depressions, sinkholes have formed, and streams disappear into the valley floors (Figure 3-5A). These sinkholes, referred to as "swallow holes" by McGill and Stromquist (1974), are commonly elongate, reflecting control by bedrock joints or faults. Swallow holes up to 20 m (60 ft) deep have been observed; they commonly provide excellent exposures of the most recent graben-filling sediments.



GRABENS AND DRAINAGE PATTERNS IN THE NEEDLES FAULT ZONE

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Figure 3–1

A

A. View south of arcuate pattern of grabens in the Needles Fault zone. Butler Wash crosses the lower left corner of the photo. Arrow points to Locality 41, a swallow hole in Cow Canyon where a soil profile (Figure 3-10) was described. Other swallow holes that can be seen in photo are noted by asterisks. The Colorado River is to the right of the photo.

B. View north of fault bounding east side of Lens Canyon, as seen from Lower Red Lake Canyon.

B

LOG 1568
REV. 0-8/15/83

STRUCTURAL FEATURES OF THE GRABENS AREA

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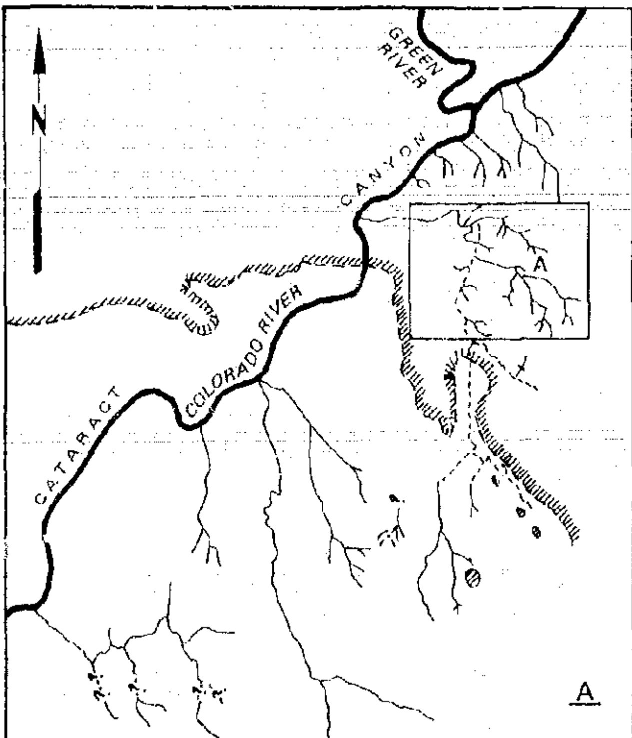
Figure 3-2

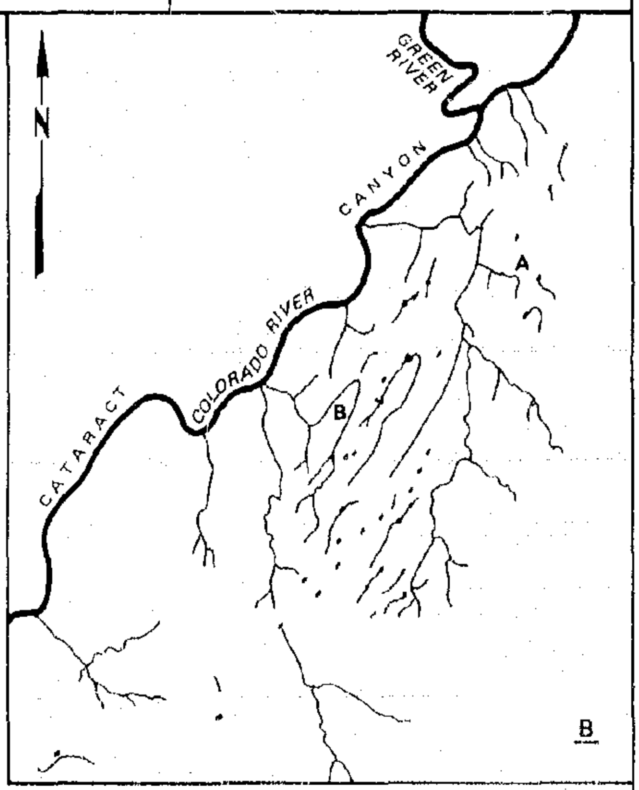


A

Drainage pattern prior to graben development in the Needles Fault zone, as inferred from abandonment channels preserved on horst blocks.
Hachured line indicates southern extent of Cedar Mesa sandstone exposures in area; lettered locality is discussed in text. Area where McGill and Stromquist (1974) originally mapped the drainage pattern prior to graben development is outlined by rectangle.

B

Present - day drainage pattern in the Needles Fault zone. Arrows indicate direction of stream flow; black elongated dots represent either swallow holes or ponded areas where internal drainages terminate. Lettered localities are discussed in text.



LOG 2261 REV.0--6/25/85	CHANGES IN DRAINAGE PATTERN DUE TO DEVELOPMENT OF NEEDLES FAULT ZONE Quaternary Topical Report	
	Project No. 17000 Woodward-Clyde Consultants	Figure 3 -3

A View west of 'hanging valley' of formerly westward-flowing stream that has been beheaded by formation of the northeast-trending Devils Lane graben.

B View northeast of Devils Lane graben. Graben valleys are typically flat-floored and filled with fine-grained sediments. Blocks of bedrock, fallen from the vertical rock walls, typically occur along the margins of the valleys. The interior drainage in this graben ends in low-lying area indicated by arrow.

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ABANDONED AND MODERN DRAINAGE SYSTEMS IN THE GRABENS AREA

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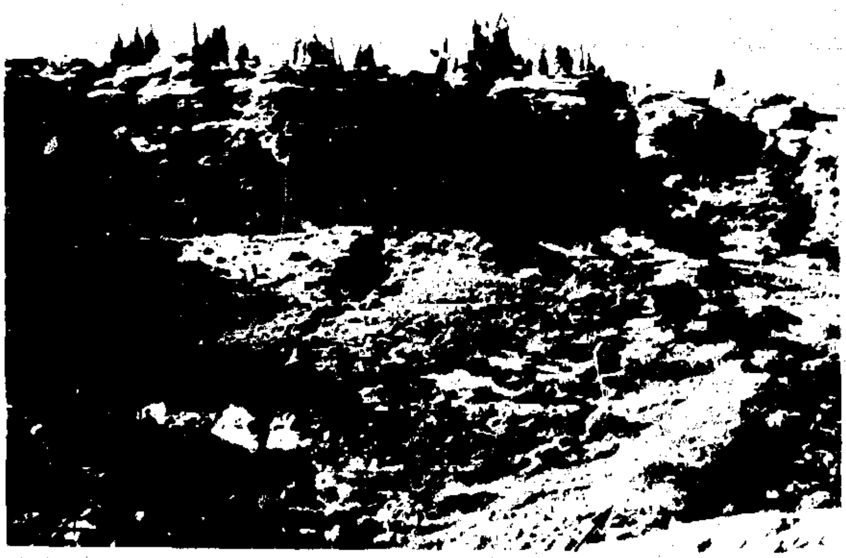
Figure 3-4

A

A. View south of swallow hole formed along graben wall at northern end of Cow Canyon. A fallen block of bedrock is indicated by the arrow. Bedding in exposed sediments ranges from laminated to massive.

B. View south of fissure that has formed east of Devils Lane. Embankment for stock pond, indicated by arrows, is downstream of fissure and was apparently constructed before its formation. Fissure is aligned with prominent joint in bedrock to the south.

B



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SWALLOW HOLES AND OPEN FISSURE IN THE GRABENS AREA

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Figure 3-5

At some swallow hole locations, open chasms in the bedrock can be seen beneath the alluvial fill. Lewis and Campbell (1965) report 2-m (7-ft)-wide bedrock separation, and that cattlemen have noticed the development of fault-line sinks since ranching began in the area. During this study, an apparently recent fissure was observed near Devils Lane (Figure 3-3, Locality A). The opening is upstream of an embankment built for watering stock (Figure 3-5B), and water that would have been impounded by the embankment now drains, in part, into a bedrock fissure that is approximately 0.5 m (1.5 ft) wide.

The pregraben drainage network identified in aerial photographs is shown on Figure 3-3A, following the technique originally reported in McGill and Stromquist (1974). Preserved abandoned channels in the northern part of the fault zone are confined to the resistant, extensively jointed, Cedar Mesa Sandstone tongue that crops out in that area. The lack of evidence of pregraben drainages in the central part of the area may be due to the less resistant nature of the Cutler Formation, which crops out there. Enough time has passed since initiation of graben formation to have removed evidence of any former stream channels in this area.

Another area where few abandoned channels are visible on aerial photographs is on the block bounded by Lower Red Lake Canyon, the Colorado River, and Red Lake Canyon (Figure 3-1). This area is capped by Cedar Mesa Sandstone, in which channels are well preserved to the east. The lack of abandoned drainages west of Red Lake Canyon suggests that the Red Lake Canyon graben was one of the initial grabens to form, and that it intercepted streams flowing from the east. Therefore, the grabens east of Red Lake Canyon (Cyclone Canyon, Devils Lane, and Devils Pocket) did not form until streams that emptied into Red Lake Canyon graben had had time to become incised into the Cedar Mesa Sandstone.

In addition to the apparent youthfulness of grabens eastward from the river, McGill and Stromquist (1974) used the pregraben drainage pattern to infer that graben formation has also progressed in a northward direction. Drainages on the northern end of the Needles Fault zone appear less adjusted to graben development than those farther south, as evidenced by the extent of internal drainage, and the preservation of abandoned (hanging) stream channels on the horst blocks. In the southern portion of the area, streams such as a tributary to Y Canyon have partially adjusted their courses to follow graben valleys (Figure 3-3B, Locality B). The resulting drainage pattern is strongly rectilinear, reflecting the influence of graben structure on the stream courses (Figure 3-1).

The channels of the larger streams, such as Chesler Canyon and Butler Wash, show only minor control by the graben structures. Although these streams have maintained their courses across the graben structures, they have contributed noticeable alluvial fill to the graben valleys as they encounter the western bedrock wall of downdropping grabens. In Cross Canyon, at Locality 45, the stream flowing into the graben from the east disappears into swallow holes and no longer flows out westward through the well-defined channel, whose floor is now 1 to 2 m (3 to 6 ft) above the graben floor.

The drainage anomalies and other geomorphic features observed in the Needles Fault zone can be used to date the recency of graben development. McGill and Stromquist (1974) estimate that graben formation began around

500,000 years ago, based on an estimated rate of incision by the Colorado River, and the depth to the Paradox member beneath the river. These authors also refer to the good preservation of abandoned drainages and the persistence of internal drainage as indications of the youthfulness of the faulting. Although the swallow holes have been presented as evidence of recent graben development by extension of the subsurface bedrock units (McGill and Stromquist, 1974; Stromquist, 1976; Lewis and Campbell, 1965), surveying or instrumental data would be required to verify this theory.

An alternate explanation for the historical appearance of swallow holes is that bedrock separation occurred long ago and the open fractures subsequently were filled with windblown and/or alluvial material. The right combination of surface drainage and subsurface piping action could flush the sediments, again creating open fissures and swallow holes, and the filling process would start anew. Sediment influx into a graben may fill and eventually cover a swallow hole, whereas piping action of surface water through the fill and bedrock fractures can cause the formation of new swallow holes (Figure 3-6). Therefore, the geomorphic features that are most indicative of recency of graben development are the internal drainage system, beheaded streams, the lack of through-flowing streams to the Colorado River, and the ponding of sediments against the western walls of grabens.

3.2 GRABEN-FILLING MATERIALS

Exposures of graben-filling sediments in swallow holes reveal a combination of colluvial, eolian, and alluvial deposits. At some localities, large sandstone blocks up to 10 m (33 ft) in diameter have fallen from the graben walls and have been, or are being, buried by the fill deposits. Fine-grained sediments, consisting primarily of massive sand with layers of angular pebbles, have filled in the spaces adjacent to the blocks. The extent of soil development observed in the fine-grained fill varies from the total absence of buried soils at most localities, indicating that deposition has been continuous and/or relatively rapid; to weak calcic horizons, suggesting episodic filling of the swallow hole; to buried, moderately developed, calcic and argillic soils. The graben fill was examined and sampled for age analyses at five locations (Figure 3-1, Table 3-1). Samples were collected for radiocarbon and thermoluminescence (TL) age analyses at all five localities. Soil profiles were described and sampled for pedogenic carbonate content at two localities (40 and 41, Figure 3-1). The stratigraphy and laboratory results for the five sites are discussed in the following sections.

3.2.1 Cross Canyon, Locality 45

The swallow hole formed at the intersection of Cross Canyon with the northeastern end of Imperial Valley (Locality 45, Figure 3-1; Figure 3-7) exposes three major sedimentary units that document progressive ponding of drainage and recent deformation of graben-filling sediments. The oldest sediments exposed consist of approximately 5 m (17 ft) of pebbly sand, sand, and cobbles (Figure 3-8), and are indicative of unrestricted stream flow. Two buried clay-rich horizons, interpreted as pedogenic in origin, were observed. The uppermost is overlain with 1.5 m (5 ft) of eolian sand. A radiocarbon date of 1,020±520 years before present (BP) (WSU-2768) was obtained from

Cemented colluvium filling bounding fault of a graben structure along the Colorado River (Sec. 34, T30½S, R18E) in the Needles Fault zone. A similar feature was observed in Cross Canyon, one mile upstream from its confluence with the Colorado River.

	COLLUVIUM-FILLED FRACTURE, NEEDLES FAULT ZONE	
	Quaternary Topical Report	
LOG 991 REV. 1 9/18/85	Project No 17000 **Woodward-Clyde Consultants**	Figure 3–6

Table 3-1. Age Estimates and Dates From Surficial Deposits in the Needles Fault Zone

Locality	Site Location	Sample	Dating Technique: Carbon-14; Sample Size (g)	Dating Technique: TL	Dating Technique: Ped. $CaCO_3$[a]	Age (10^3 yr BP)	Lab Number	Comments
40	Sec. 9, T31S, R18E-1 Western graben	(a)		x		61.54 ± 4.67	ALPHA-526	
		(b)		x		65.37 ± 4.53	ALPHA-527	
					x	115 to 190		29 g/cm^2 estimated pedogenic $CaCO_3$ in soil profile.
41	Sec. 11, T31S, R18E-1 Cow Canyon	(a)	2.9			103% modern	WSU-2796	Chenoped seeds.
		(b)	0.08			2.76 ± 0.2	WSU-2767	Charcoal. Date derived through barium hydroxide process.[b]
		(c)		x		16.3 ± 1.47	ALPHA-468	
		--			x	70 to 115		17 g/cm^2 estimated pedogenic $CaCo_3$ in soil profile.
42	Sec. 11, T31S, R18E-2 Cow Canyon	(a)	0.85		x	2.45 ± 0.21	WSU-2797	Charcoal.
44	Sec. 14, T31S, R18E-2 Cow Canyon	(a)	5			0.3 ± 0.065	WSU-2766	Organic matter.
		(b)		x		3.22 ± 0.29	ALPHA-528	
		(c)	0.6			3.91 ± 0.69	WSU-2764	Charcoal.
		(d)	1.5			110% modern	WSU-2763	Wood.
		(e)	1.1			2.70 ± 0.22	WSU-2765	Charcoal.
45	Sec. 28, T31S, R18E-1 Cross Canyon	(a)	8.0			102% modern	WSU-2795	Wood.
		(b)		x		11.56 ± 1.08	ALPHA-531	
		(c)	0.5			6.42 ± 0.73	WSU-2794	Charcoal.
		(d)		x		16.3 ± 1.26	ALPHA-529	
		(e)		x		46.3 ± 4.63	ALPHA-530	
		(f)	1.5			1.020 ± 0.52	WSU-2768	Charcoal.

Note: See Figures 3-8 and 3-11 for schematic stratigraphy and location of sampling sites at individual localities.

(a) Pedogenic calcic soil ages based on estimated carbonate influx rates of 0.15 to 0.25 g/cm^2/1,000 years.

(b) The barium hydroxide process is described in Section 4.1.2.

A. View south of swallow hole in Cross Canyon (Locality 45). Arrow denotes person for scale. Mud cracks can be seen in bottom of pit.

B. Upper part of oldest sediments exposed in swallow hole in Cross Canyon. Hammer is near collection site of TL sample dated at 46,300 ± 4,630 years BP.

DEPOSITS EXPOSED IN SWALLOW HOLE NEAR CROSS CANYON

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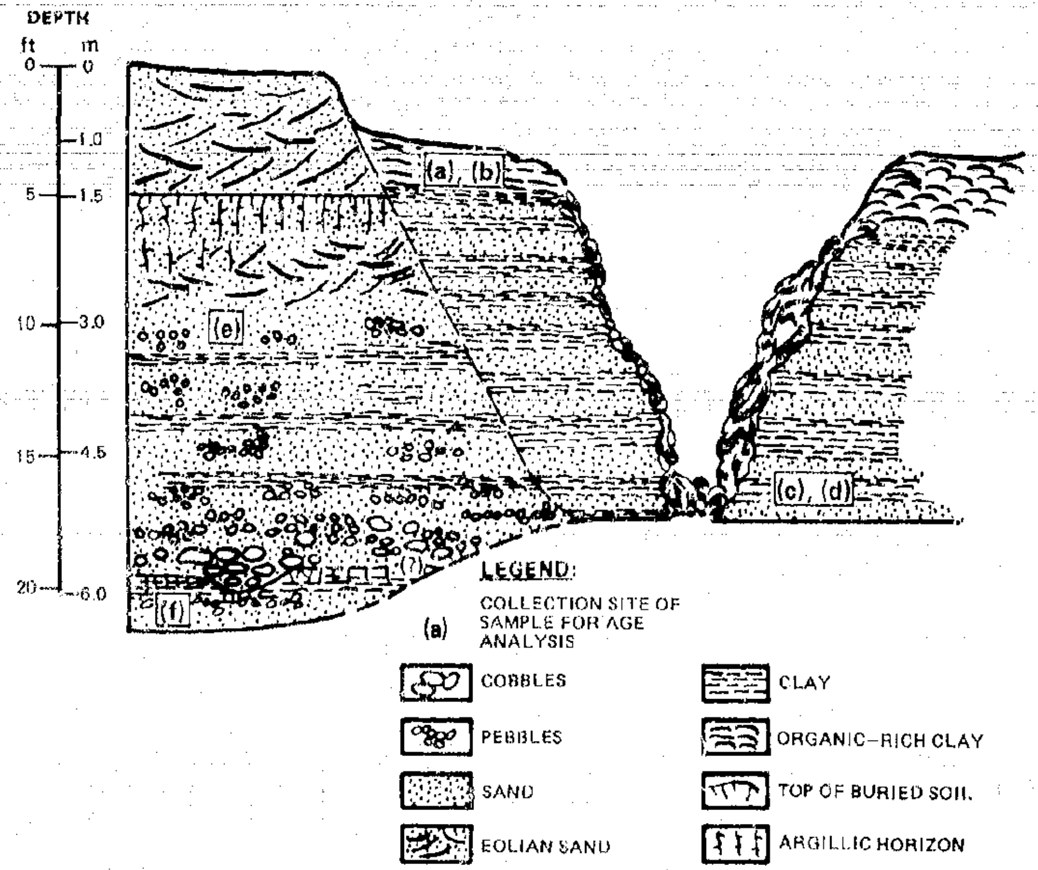
Figure 3-7



DERIVED DATES (years BP)

(a) ^{14}C: 102% MODERN

(b) TL: 11,560 ± 1,080

(c) ^{14}C: 6,420 ± 730

(d) TL: 16,300 ± 1,260

(e) TL: 46,300 ± 4,630

(f) ^{14}C: 1,020 ± 520

See Table 3–1 for additional data regarding samples.

SCHEMATIC CROSS SECTION OF QUATERNARY SEDIMENTS EXPOSED IN SWALLOW HOLE, CROSS CANYON LOCALITY 45

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Figure 3-8

charcoal at the base of the exposure, and a TL date of 46,300±4,630 years (ALPHA-530) was obtained from sediments near the top of the oldest unit (Figures 3-7B and 3-8, Table 3-1).

A younger unit, consisting of at least 4.6 m (15 ft) of rhythmically bedded sands and clays, fills a channel cut into the older unit (Figure 3-7). Mud-cracked clay layers that occur at the top of most cycles appear to represent a more restricted stream flow than in the older unit and indicate that flow was at least periodically ponded. A date of 6,420±730 years BP (WSU-2794) has been derived from charcoal collected from the base of these sediments; sediments from the same horizon yielded a TL date of 16,300±1,260 years (ALPHA-529) (Figure 3-8, Table 3-1).

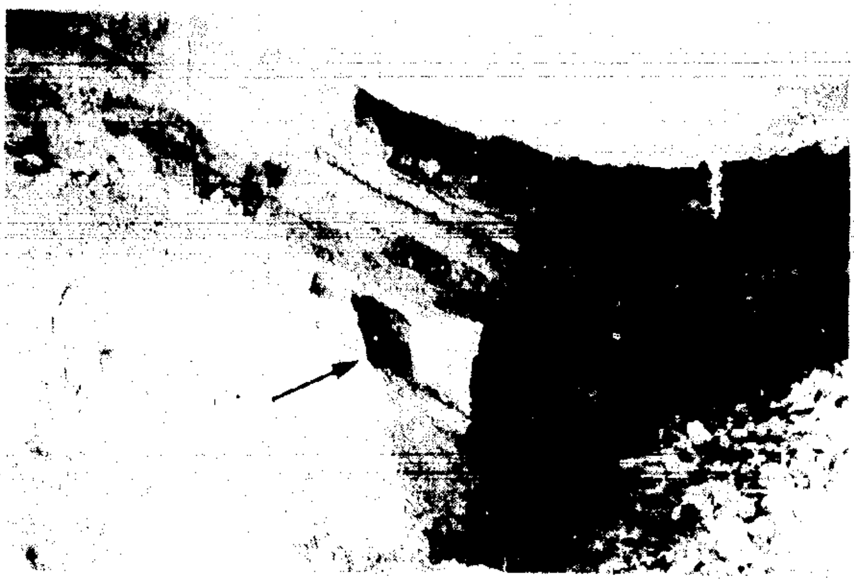
The uppermost unit in the Cross Canyon swallow hole consists of approximately 1 m (3 ft) of finely layered, matted organic debris interbedded with thin sandy layers. Flow during deposition of the uppermost unit was apparently more restricted than that associated with deposition of the middle unit. The lower half of these sediments is downwarped, whereas the uppermost strata are horizontal (Figure 3-9A). A carbon-14 (^{14}C) date of "103 percent modern" (WSU-2796) was obtained from organic debris at the base of this unit. A TL date of 11,560±1,080 years (ALPHA-531) was derived from silt deposits, also at the base of the unit.

The age-dating samples were collected to provide both an age of the deposit and a comparison between the radiocarbon and TL dating methods. Two samples (one for each of the techniques) were collected from each of the three units. There is no agreement between the derived dates for any of the sample sets. The TL dates are stratigraphically reasonable, whereas the lowermost ^{14}C date (Sample f, Figure 3-8) is too young, both in view of the paleosols present in the profile, and when compared with the other derived dates. With the present amount of data, it is not possible to judge which set of dates most accurately reflects the actual age of the two younger deposits. The two soils observed in the oldest unit support the derived TL date of 46,300 years BP; however, they are not sufficiently developed to suggest that the deposit is significantly older than 50,000 years BP.

The character of the deposits indicate that ponding of the Cross Canyon stream and the development of swallow holes did not occur until after the oldest exposed unit was deposited. The cobble-size clasts in the oldest deposits are indicative of a higher velocity than that of the present-day stream upstream of Locality 45 in Cross Canyon. Alternatively, graben formation may have already begun, but the stream was able to maintain flow across the western lip of the graben. A modern analog may be seen in the area where the jeep road crosses the wash south of Butler Wash (E on Figure 3-1).

A swallow hole at least 5 m (17 ft) deep subsequently developed in these deposits and was filled with material indicative of restricted stream flow. The lack of cobbles in these deposits suggests that the velocity of water flowing into the swallow hole was significantly lower than that which deposited the older material. The downwarping of the uppermost fill probably reflects the opening of a void beneath the deposits while they were accumulating. The opening was not sufficiently large to cause collapse of the strata exposed in the modern swallow hole, and the surface depression formed by the deformation was progressively filled with organic-rich clay.

A



A. Sand deposits and thin beds of matted organic debris downwarped into a gulley on west side of Cross Canyon swallow hole (Locality 45). Arrow shows collection site of radiocarbon and TL age dating samples. The derived TL date is 11,560±1,080 years BP; the ^{14}C date is 102% modern.

B

B. View north of uppermost portion of sediments that have accumulated in a graben in the western part of the Needles Fault zone (Locality 40). Massive units exposed near person (arrow) are probably eolian in origin. They are overlain by thinner, bedded sand and cobbly colluvium. Basal fluvial deposits were observed at stream level, where a TL date of 65,370±4,530 years BP was obtained. A TL date of 61,540 ± 4,670 years BP was derived near the top of the overlying eolian material (See Figure 3-11).

GRABEN-FILLING DEPOSITS

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Figure 3-9

The deposits observed in the Cross Canyon swallow hole indicate that deposition in the Needles Fault zone is complex. Extensional bedrock deformation has provided an underground "plumbing" system into which streams flowing into the grabens can totally disappear. Swallow holes can develop by either the continual widening of the pull-apart bedrock fractures, or by the flushing (or piping) of fracture fill from underneath. Once a hole has developed, the subsurface drain could be plugged by a high influx of sediment, and a hole might develop elsewhere along the fissure. However, the original location may eventually again be the site of subsequent collapse and inflow.

3.2.2 Cow Canyon

The upper 3 m (10 ft) of graben-filling sediments are exposed (1) in a swallow hole in the center of Cow Canyon (Locality 41, Figure 3-1); (2) in a 4-m (12-ft)-deep swallow hole along the northwestern edge of Cow Canyon (Locality 42); and (3) in a series of swallow holes, up to 6 m (20 ft) deep, near the intersection of Cow Canyon and a branching graben to the east (Locality 44). Samples were collected at these swallow holes to assess the age of the graben fill in Cow Canyon. A soil profile was described and sampled at Locality 41. The samples obtained were analyzed for carbonate content and particle size distribution (Figure 3-10). Additionally, two charcoal samples were collected for radiocarbon dating from both above and below the calcic soil horizon. Another sample stratigraphically below the lower charcoal sample was collected for TL dating. At Locality 42, charcoal was collected at a depth of approximately 3 m (9 ft). The stratigraphic settings of the multiple samples collected from Localities 41 and 44 are shown in Figure 3-11.

3.2.2.1 Locality 41

The swallow hole at Locality 41 is in a topographically high area, and appears to be in the center of a graben. However, the swallow hole probably occurs above the buried extension of a fault that bounds a narrower portion of the graben to the south.

The sedimentary units exposed are indicative of initial fluvial deposition, followed by a period of colluviation, with eolian deposition occurring most recently. At the base of the exposed measured section, 1.5 m (5 ft) of alternating sand and clay-rich units are exposed. The clay-rich layers contain fine organic debris. A buried soil, which exhibits an argillic B horizon and a calcic horizon (Figure 3-10), is preserved at the top of this section along the east wall of the swallow hole. Along the west wall, the B horizon is weaker and is absent in places, but the carbonate is significantly stronger (up to 1 m [3 ft] of Stage III carbonate is present).

A pebbly sand unit 1.1 m (3.5 ft) thick disconformably overlies the buried soil. This unit probably represents slope-wash deposits. The considerable relief observed on the base of this unit indicates that open cracks and gullies were probably present during deposition of this fill. A very weak (Stage I) calcic horizon is developed in this unit. A 0.8-m (2.5-ft)-thick horizon of fine eolian sand was measured above the slope-wash unit.

The derived age estimates and dates varied significantly at Locality 41. A total of 17 g/cm^2 of pedogenic carbonate was measured in the sampled soil column (Figure 3-10). Using the long-term carbonate influx rates of 0.15 to 0.25 g/cm^2/1,000 years (Section 4.1.1.4.1) that have been calculated for the area to the east and north of the Grabens (WCC, 1982a, Vol. I, p. 3-16), an age of approximately 70,000 to 115,000 years was derived for these deposits.

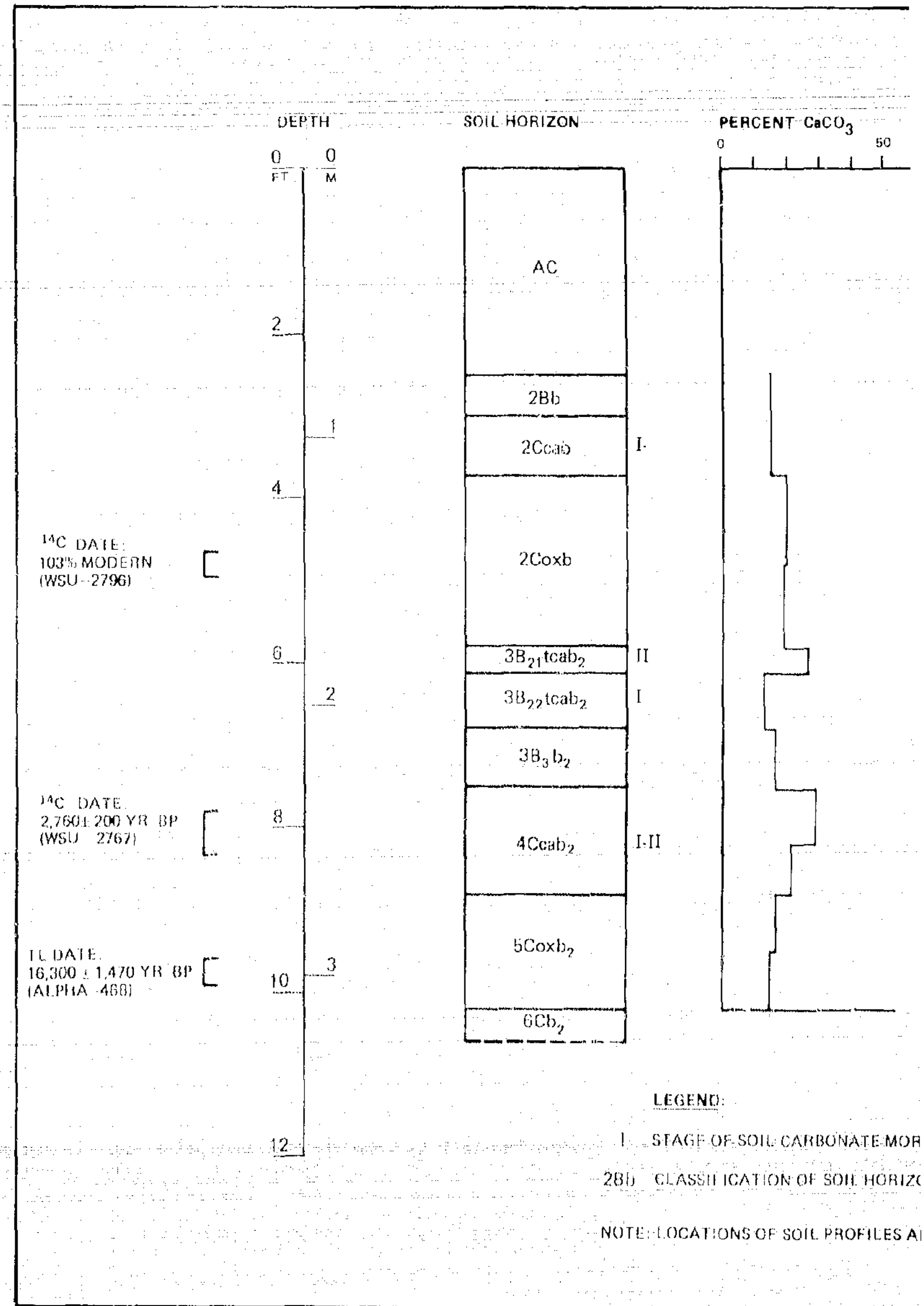
A radiocarbon date of "103 percent modern" (WSU-2796) was obtained from the charcoal collected from slope-wash deposits above the buried soil horizon; another date of 2,760±200 years BP (WSU-2767) was obtained from charcoal collected below the soil horizon. The TL sample, collected near the bottom of the exposure, provided a date of 16,300±1,470 years BP (ALPHA-468) (Table 3-1; Figures 3-10 and 3-11).

The two derived radiocarbon dates are judged to be an inaccurate reflection of the age of the deposits because of the extent of soil development in the soil profile. The "modern" sample was apparently contaminated, or a recently charred plant root; the older sample may also have been a fragment of a charred root, representing a plant living in the deposit 2,800 years ago. Alternatively, the older ^{14}C date may not be accurate because of the extremely small size of the analyzed sample (Table 3-1).

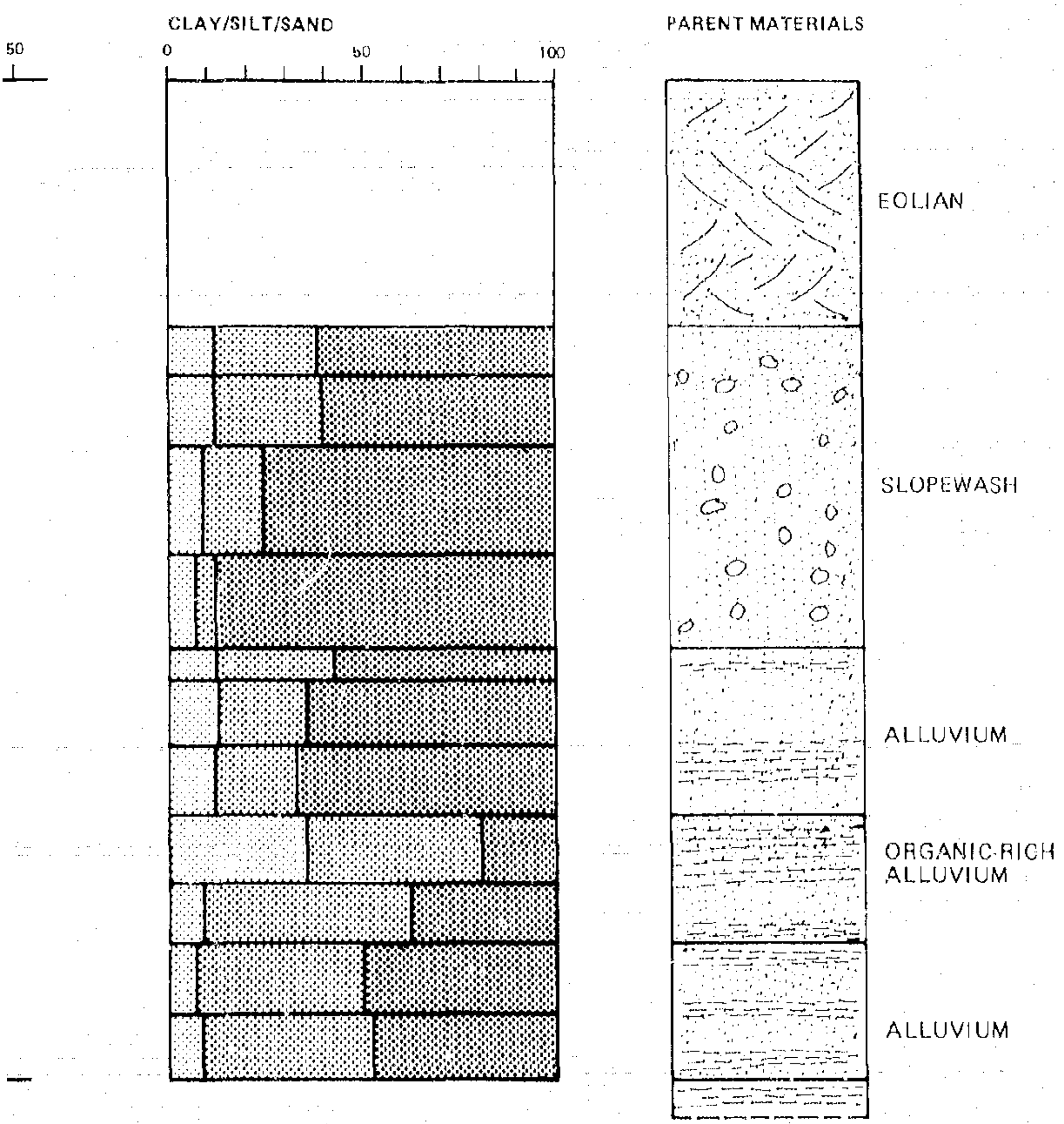
The other two dating techniques (soil carbonate accumulation and TL analysis) provide widely discrepant age estimates for the deposit. The calculated soil carbonate age of 70,000 to 115,000 years seems high, whereas, given the extent of soil development observed, the TL date of 16,300±1,470 years BP seems low. The carbonate influx rate may be abnormally high in the Grabens area because graben structures tend to trap eolian material and retain soil carbonate within their closed drainage networks. These factors may concentrate $CaCO_3$ in the soil profile, and provide an age estimate that is too high.

If the TL date is assumed to be correct, the carbonate influx rate would be approximately 1 g/cm^2/1,000 years. This rate is less than the Holocene rate of 1.39 g/cm^2/1,000 years derived for 1,300-year-old deposits near Moab, Utah (Locality 7, Spanish Valley), but twice the mean average rates reported by Machette (1985) for the last 18,000 years in southern New Mexico (Section 4.1.1.4.2). However, an influx rate of 3.84 g/cm^2/1,000 years was derived from deposits overlying a charred horizon dated 430±110 years BP (DIC-1893) in the Gibson Dome area (Locality 46). (WCC [1982, Vol. II] reported the influx rate as 4.65 g/cm^2/1,000 years.) Therefore, although the local cumulative influx rate of 1 g/cm^2/1,000 years for the Grabens area may not be unreasonable, the TL age of 16,000 years for the deposits is probably too young for the extent of soil development observed.

Without additional data on local Holocene/late Pleistocene carbonate influx rates or analysis of the accuracy of TL dates (see Section 4.3.3), the Cow Canyon deposits at Locality 41 are judged to be 16,000 to 80,000 years in age. The lower age estimate reflects the TL date obtained. The older age estimate assumes a 0.447 g/cm^2/1,000 years accumulation rate for the last 18,000 years (Machette, 1985), and rate of accumulation of 0.15 g/cm^2/1,000 years for late Pleistocene time (see Sections 4.1.1.4.1 and 4.1.1.4.2).



DEPTH
SOIL HORIZON
PERCENT $CaCO_3$
0
50
0 FT
0 M
2
1
4
6
2
8
10
3
12
AC
2Bb
2Ccab
I-
2Coxb
$3B_{21}tcab_2$
II
$3B_{22}tcab_2$
I
$3B_3b_2$
$4Ccab_2$
I-II
$5Coxb_2$
$6Cb_2$
^{14}C DATE:
103% MODERN
(WSU-2796)
^{14}C DATE
2,760 ± 200 YR BP
(WSU 2767)
TL DATE:
16,300 ± 1,470 YR BP
(ALPHA -468)
LEGEND:
I STAGE OF SOIL CARBONATE MOR
2Bb CLASSIFICATION OF SOIL HORIZ
NOTE: LOCATIONS OF SOIL PROFILES A



: MORPHOLOGY

ORIZON

.ES ARE SHOWN ON FIGURE 1 1.

SOIL PROFILE EXPOSED IN EAST WALL OF SWALLOW HOLE, MIDDLE COW CANYON LOCALITY 41

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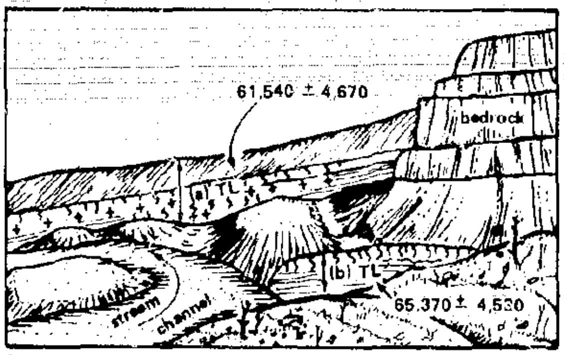
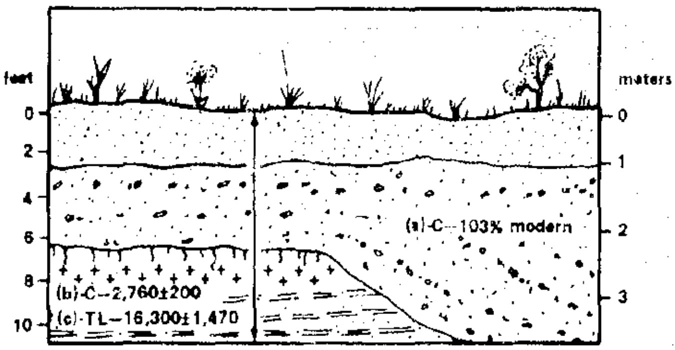
LOCALITY 40 WESTERN GRABEN*



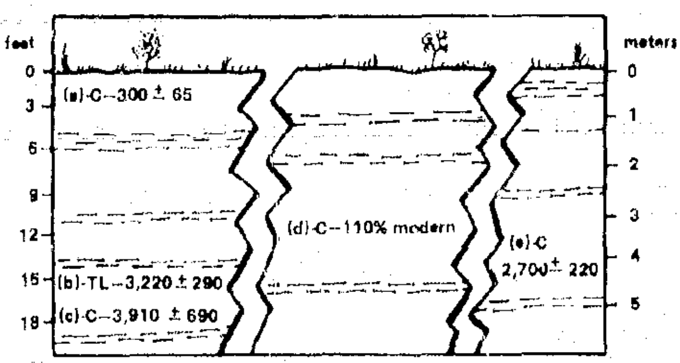
* See Figure 3–9B for photograph of deposit

LOCALITY 41–MIDDLE COW CANYON*
PROFILE MEASURED FOR PEDOGENIC CARBONATE ACCUMULATION



*See Figure 3–10 for soil profile description

LOCALITY 44–COW CANYON SOUTH



LEGEND:

BURIED B SOIL HORIZON

CALCIC SOIL HORIZON

CLAYEY-SILT DEPOSITS

SANDY DEPOSITS

(a) LOCATION OF SAMPLE COLLECTED FOR DATING STUDIES

C ^{14}C DATE

TL TL DATE

Notes:

1. Laboratory numbers for dates are given in Table 3–1
2. Schematic diagrams are not drawn to scale.
3. Dates are given as years BP.
4. See Table 3–1 for additional data regarding samples and dates.

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STRATIGRAPHIC SETTING OF DATED GEOLOGIC SAMPLES FROM THE NEEDLES FAULT ZONE
Quaternary Topical Report

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Figure 3–11

3.2.2.2 Locality 42

The character of the graben fill was also examined at Locality 42, 0.6 km (0.35 mi) northwest of Locality 41 (Figure 3-1), where a swallow hole has developed along the western edge of the Cow Canyon graben, exposing approximately 4 m (12 ft) of sandy deposits. Layers of angular pebbles are common, and the fill resembles the slope-wash deposit at Locality 41. Fine-grained horizons containing organic debris are much less common than at Locality 41. Along the northern wall of the exposure, large colluvial blocks of bedrock have been buried by fine-grained deposits.

At Locality 42, a date of 2,450±210 years BP (WSU-2797) was obtained from charcoal collected at a depth of approximately 3 m (9 ft). The stratigraphy exposed in the swallow hole consisted of fine- to medium-bedded sand, silt, and pebble layers. Other means of quantitatively assessing the accuracy of this radiocarbon date are not available. However, the date is judged reasonable because of the observed youthfulness of the deposits, which were unconsolidated and lacked discernible pedogenic development.

3.2.2.3 Locality 44

Locality 44 is 1.2 km (0.75 mi) southwest of Locality 41 (Figure 3-1), and consists of a series of swallow holes formed along a bedrock wall, near the intersection of Cow Canyon and a branching graben to the east. Approximately 6 m (20 ft) of thin- to medium-bedded sand, clayey silt, and infrequent layers of small pebbles, clay, or organic material are exposed. Four ^{14}C samples and one TL sample were collected to date deposits from the three different swallow holes.

A TL date and a ^{14}C date from samples collected at a depth of 5 m (16 feet), and having a vertical separation of 0.3 m (1 ft), have concordant results of 3,220±290 years BP (ALPHA-528) and 3,910±690 years BP (WSU-2764), respectively. Charcoal collected at a shallower depth (3.7 m [12 ft]) in a nearby swallow hole yielded a ^{14}C date of 2,700±220 years BP (WSU-2765). One other informative date, 300±65 years BP (WSU-2766), was derived from organic debris collected 0.5 m (1.5 ft) below the ground surface.

Locality 44 is in a topographically low area of the graben, and presently receives runoff from a limited local area. The radiocarbon and TL dates from that area are stratigraphically reasonable and in agreement, with the exception of one "modern" date that suggests sample contamination. The dates are assessed as providing an accurate age assessment of the deposits at this locality.

3.2.2.4 Summary, Cow Canyon

The age dates indicate that the upper 5 m (16 ft) of fill exposed in the swallow holes in the topographically lower northern and southern parts of Cow Canyon are of late Holocene age (less than 4,000 years old). The sedimentation rates derived at these localities vary from 1.2 m to 1.7 m (3.9 to 5.6 ft) per 1,000 years. Although these areas are now actively eroding, no evidence of a previous episode of swallow-hole development and subsequent refilling of the depression was seen. Such evidence was observed in the middle of Cow Canyon (Locality 41), and at Cross Canyon (Locality 45, Section 3.2.1). However, this may be due to the fortuitous location of the present swallow holes.

The swallow hole in the middle of Cow Canyon (Locality 41) exposes an older sequence of deposits than was observed at either Localities 42 or 44. The hole is in a topographically high area, and therefore presently receives only eolian material and very little waterborne sediment. However, the alluvial and slope-wash deposits observed in the lower half of the profile indicate that this part of the graben has been subject to fluvial flow conditions as recently as 16,000 or as early as 75,000 years ago. The lower half of the profile shown in Figures 3-10 and 3-11 is characterized by argillic soil horizons, indicating at least a probable late Pleistocene age for the deposits.

3.2.3 Western Graben, Locality 40

Deposits filling one of the westernmost (and theoretically oldest) grabens are exposed in a stream meander at Locality 40 (Figures 3-1 and 3-9). The lowermost stratum in the exposure consists of flat-lying, well-sorted fluvial deposits; eolian and colluvial deposits comprise the remaining overlying deposits (Figure 3-11). Two buried soils were observed in the exposure both characterized by argillic and calcic soil horizons. The lower soil has formed in the fluvial deposits near the base of the exposure, and the other is in an eolian/colluvial unit.

Two samples were collected for dating by TL analysis; no material suitable for radiocarbon dating was observed. A TL date of 65,370$\pm$4,530 years BP (Alpha-527) was derived from the fluvial deposits at the base of the exposure (Figure 3-10B). The other date of 61,540$\pm$4,670 years BP (Alpha-526) was obtained from the argillic soil horizon in a massive sandy unit of probable eolian origin in the middle of the exposure. The dates are therefore stratigraphically consistent.

Samples were also collected throughout the exposure to estimate the age of the deposits by calcic soil development. Laboratory analyses of the samples indicate that 29 g/cm^2 of pedogenic $CaCO_3$ have accumulated in the soil profile (Table 3-1). Using regional carbonate influx rates of 0.15 to 0.25 g/cm^2/1,000 years (Section 4.1.1.4.1), a date of approximately 115,000 to 195,000 years BP was obtained for the deposit. As discussed in Section 3.2.2.1, soil carbonate data collected at Locality 41 in the Grabens area suggest that carbonate influx rates in the area may be higher than the regional trend, perhaps because of the natural traps formed by the graben structures. When an influx rate of 0.447 g/cm^2/1,000 years is assumed for the last 18,000 years (Section 3.2.2.1) and regional rates of 0.15 to 0.25 g/cm^2/1,000 years (Section 4.1.1.4.1) are applied to earlier Pleistocene time, an age range of 100,000 to 160,000 years is obtained. If the TL dates are assumed correct, the average, long-term rate for carbonate influx is on the order of 0.46 g/cm^2/1,000 years. Applying the long-term influx rate obtained at Locality 41, 1 g/cm^2/1,000 years, the deposits at Locality 45 would be only 29,000 years old.

The dates obtained for the deposits exposed at Locality 40 indicate that they are probably older than material exposed in Cow and Cross Canyons. This interpretation is supported by the presence of two buried soils, the greater amount of soil carbonate in the deposits, and two consistent TL dates. The TL dates are judged to be reasonably accurate, placing the age of the deposit at approximately 60,000 to 65,000 years. The age range indicated by the soil carbonate data, 29,000 to 160,000 years, using influx rates that are higher than the assumed regional rates, brackets the TL dates, but cannot be used to assess the accuracy of the TL dates because of the uncertainty of the soil carbonate influx rate applicable to the Grabens area.

3.3 ESTIMATED RATE OF GRABEN FORMATION

The rate of graben development can be assessed by estimating the time of initial graben formation. As discussed earlier, grabens in the northern and eastern areas of the Needles Fault zone appear to be more recently formed than those to the south and west, respectively. The time of canyon development can be used to estimate the rate of graben formation from west to east. The upper limit is provided by the age of Cataract Canyon. The canyon is 341 m (1,120 ft) deep. Assuming the conservative (i.e., probably too high) river incision rate of 0.24 m (0.8 ft) per 1,000 years (WCC, 1982a, Vol. 1), Cataract Canyon began forming approximately 1.4 million years ago, and graben development would have started at a later time.

The lower limit is more difficult to define. At the present time, the oldest date that has been derived for samples collected from Quaternary sediments accumulated in the downdropped graben structures is approximately 65,000 years BP (Section 3.2.3). Because of the lack of other age data, this date has been used to define the minimum age of the grabens. The graben from which the dated sample was collected is located 3.2 km (2 mi) from the river, in an area where the entire graben system is 12 km (7.5 mi) wide. The sample was collected from probable eolian (dune) deposits along the eastern margin of a downdropped graben block. The eolian deposits were subsequently buried by colluvium derived from the adjacent horst block.

Development of the overall graben system would have actually begun prior to 65,000 years ago in order for the graben in which the sample was collected to have formed, and for graben development to have progressed eastward from the river to the sampling site. As described above, the sample site is located 3.2 km (2 mi) from the river, and the entire graben system is 12 km (7.5 mi) wide at this point. Assuming that, through time, graben development has progressed linearly eastward from the river, the 65,000-year-old date reflects the minimum time in which 25 percent of the system had formed. This approach results in a calculated minimum age of approximately 85,000 years for the graben system.

The estimated range for the age of the graben system provides a means of bracketing the rates at which the grabens have developed. Given the assumption that mass movement processes (and hence, graben formation) did not begin until after 1.4 million years ago, and that they have developed over a distance of 7.2 km (4.5 mi) since then, the lower bound on the rate of graben formation is 5 m (17 ft) per 1,000 years. The upper limit on the rate of graben growth is provided by the assumption that graben development began

85,000 years BP and has progressed eastward over a distance of 12 km (7.5 mi) from the river. These parameters provide a maximum rate of graben development of approximately 140 m (465 ft) per 1,000 years. The rate of graben development from south to north cannot readily be estimated.

3.4 SUMMARY AND RECOMMENDATIONS

Reconnaissance-level observations conducted during the Paradox Basin studies support the theory that graben formation is an ongoing process. The geomorphic expression of drainage changes indicates that the grabens may be younger in the northern portion of the area than in the south. The pattern of complex, coalescing graben valleys along the Colorado River, and simple linear structures along the eastern margin of the area also suggests that graben formation has proceeded eastward, away from the river (McGill and Stromquist, 1974). A crude and conservative (i.e., high) estimate of the rate at which the graben may have spread eastward is 5 to 140 m (17 to 465 ft) per 1,000 years.

The effect of graben formation is recorded by the geomorphology and in the Quaternary fill deposits. Some exposures provide evidence that streams initially flowed freely across this area, and progressive restriction and eventual ponding of the stream flow occurred. In most exposures, only the effects of ponding were recorded in the deposits. Preliminary evidence suggests that swallow hole features may be regularly created and filled, then re-created above graben-bounding faults. Swallow-hole formation may be caused either by expansion (opening) of faults due to downdip gravity sliding of the Needles bedrock mass, or by piping and flushing of sediments from open subsurface fractures formed by the boundary faults. The bedrock floor of the graben was not observed in any of the swallow holes examined. Therefore, the deposits exposed in the swallow holes postdate, and provide only minimum dates for, graben formation.

Age data indicate that the oldest deposits studied are approximately 60,000 to 65,000 years old, and are exposed in one of the western grabens (Locality 40). It is unlikely that the oldest basal graben deposits, which could provide control on the age of the grabens, and hence a means of estimating the rate of graben formation, will be seen in surface exposures. The swallow holes and streambank exposures provide access to only the upper 6 m (20 ft) of material at a limited number of locations. Geophysical investigative techniques would be required to learn the depth and geometry of the graben fill. Samples for geologic dating might be acquired from basal deposits through the use of a coring device; samples taken at incremental depths would provide a means of evaluating the accuracy of derived dates. Uranium-trend dating is the most definitive dating method applicable to the graben deposits; however, it is not commercially available. Of those techniques that are commercially available, the radiocarbon and TL dating methods and paleomagnetic analysis appear most applicable to assessing the age of graben deposits. Horizons of organic debris (twigs, leaves, etc.) found in the ponded deposits generally provide an adequate amount of sample for radiocarbon analyses, and should accurately provide a date for the deposit if it is less than 35,000 years old. The TL method provided stratigraphically and (generally) geologically reasonable dates in the preliminary study. However, because the dating method is relatively new, duplicate dating is recommended to verify the derived dates. Paleomagnetic analysis could be used to determine if the deposits are older or younger than 730,000 years BP.

Age assessments based on calcic soil development provide a broad age range due to the uncertainty in the carbonate influx rate for the area. If the TL dates are assumed accurate at the two localities where soil carbonate accumulation was measured, long-term influx rates of 1 $g/cm^2/1,000$ years and 0.46 $g/cm^2/1,000$ years are obtained. The long-term rates calculated previously are 0.15 to 0.25 $g/cm^2/1,000$ years. The internal drainage and the natural topographic traps formed by the grabens may contribute to unusually high (also locally varied) carbonate accumulation rates in the Needles Fault zone. Until better age control is obtained for calculating influx rates, calcic soil development is useful in providing only a broad age assessment for deposits in this area.

4.0 METHODS USED TO DATE QUATERNARY DEPOSITS

As part of the Quaternary studies of the Paradox Basin in Utah, various age dating techniques were used and evaluated in assessing the age of Quaternary deposits and events in the Paradox Basin. A list of techniques incorporated in the dating program, and described in this section, is presented in Table 4-1. It includes commonly used methods, such as carbon-14 (^{14}C) analysis, as well as new techniques that have only recently become available on a commercial basis. The results of the dating studies, including their applicability and recommendations for future studies, are discussed in this chapter. All of the age data collected from the sites shown on Figure 1-1 are presented in Table 1-1.

The ages of specific geologic deposits are of interest to the project because the dates provide the means of (1) assessing the timing, rate, and recurrence of geologic processes and climatic events that have occurred during Quaternary time; and (2) addressing the potential effect of future geologic and climatic changes on the integrity of an underground high-level nuclear waste repository during its lifetime. Specific geologic processes include bedrock incision and scarp retreat; and erosional, depositional, and hydrologic changes that occur during glacial-interglacial cycles. Age data are also used to evaluate the tectonic stability and salt dissolution history of an area, and the activity of faults in the vicinity of the potentially acceptable repository site.

4.1 TECHNIQUES FOR PROVIDING AGE CONTROL

The geologic dating program developed for the Paradox Basin studies incorporated a phased approach that included an initial evaluation of each technique to assess its usefulness to the Paradox Basin setting. To assess the accuracy of the various techniques, initial samples submitted for dating were those for which the approximate age or relative ages were known. Additionally, to test the validity of the dates derived by various methods, samples from one or more locations were dated by a number of techniques, such as radiocarbon (^{14}C), thermoluminescence (TL), and amino acid analyses; and measurement of soil carbonate. When the results of a specific technique appeared reasonable, additional samples of unknown age were submitted for dating by that method. The geologic setting and history of the dated sample were reviewed before the obtained date was judged valid.

Some of the age dating techniques listed in Table 4-1 have been used extensively in the scientific community and are generally considered to be well understood and accepted. However, suitable materials, or materials of the applicable age range are not always available in the Paradox Basin for the more accepted methods, so alternate dating approaches were considered. These alternate techniques have been recently reported in the literature but have not been extensively applied. Section 4.1 of the report presents (1) the basis and reported application of dating methods that were subsequently used in this project, (2) the derived data, (3) a discussion of the means used to evaluate the accuracy of derived age data, and (4) an evaluation of the reproducibility of these results. Section 4.2 compares dates derived by multiple techniques in specific geographical areas. The accuracy and

Table B-1. Potential Age Dating Techniques for Quaternary Deposits, Paradox Basin
(Page 1 of 2)

Technique	Age-Dependent Process	Materials	Potential Age Range (years)
Pedogenesis	Weathering, influx of airborne materials	Soil	300 to early Pleistocene time
Carbon-14	Radioactive decay	Charcoal, wood, shell, bone, calcic soil	100 to 35,000 (potentially 70,000)
Thermoluminescence	Energy buildup in crystal imperfections caused by radioactive decay	Calcium carbonate, quartz, feldspar	2,000 to 250,000 (possibly 1,000,000)
Amino Acid Analysis	Epimerization of organic compounds to equilibrium ratios	Carbonate shells and organic material trapped in soil	100 to 1,000,000
Paleomagnetism	Past magnetic pole positions	Detrital iron oxide minerals in sediments; secondary magnetic minerals formed from iron-bearing minerals	Most commonly used to indicate whether deposit is older than 730,000 years.
Uranium Series	Radioactive decay	Calcium carbonate	5,000 to 300,000
Relative Weathering	Weathering	Mineral grains and gravel clasts	10,000 to 100,000

Table 4-1. Potential Age Dating Techniques for Quaternary Deposits, Paradox Basin
(Page 2 of 2)

Technique	Age-Dependent Process	Materials	Potential Age Range (years)
Topographic Position	Erosion, incision	Alluvial, glacial deposits; landforms (surfaces, strath terraces)	0 to Tertiary time
Paleontology	Evolution, environmental effects	Fossil organisms	Useful throughout Quaternary time
Palynology	Environment	Pollen	0 to 150,000
Tephrochronology	Volcanic eruptions	Volcanic ash	More than 0
Dendrochronology	Annual ring growth of trees	Wood	0 to 9,000

Sources: Colman and Pierce (1977); Packer et al., (1975).

applicability of the various methods, and recommendations regarding their use in future Quaternary studies are summarized in Section 4.3.

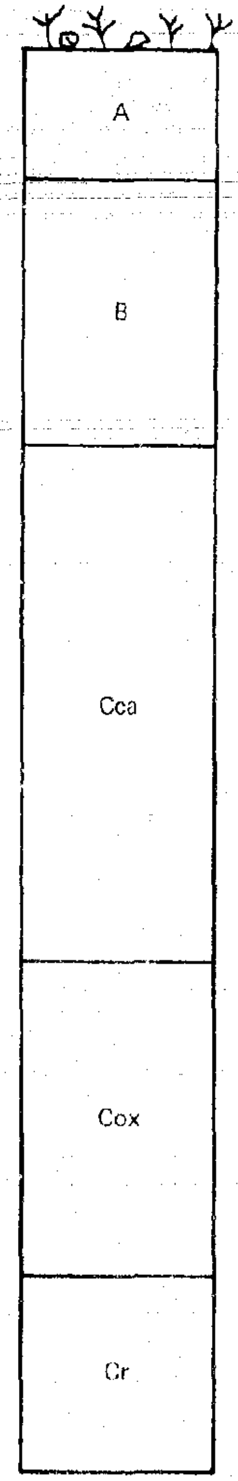
4.1.1 Pedogenesis

The degree of soil development on Quaternary deposits provides a means of assessing the length of time since a stable geomorphic surface developed on the deposits. Pedogenesis (soil development) occurs as a result of (1) in situ chemical weathering of mineral grains, (2) eolian influx of dust-size particles, and (3) downward translocation and accumulation of materials by repeated wetting and drying of the soil column (Jenny, 1980; McFadden and Wells, 1985). As these processes proceed, soil horizons with distinct physical and chemical properties develop (Figure 4-1). Many soil properties exhibit progressive development with age and are therefore useful indicators of the relative age of the underlying parent material (Marchand et al., 1979). Two soil properties that proved useful in correlating Quaternary deposits in the Paradox Basin are the accumulation of carbonate ($CaCO_3$) in soil profiles, and the buildup of clay in the B soil horizons. However, because the B horizons of many soils in the Paradox Basin have apparently been removed by erosion, the accumulation of $CaCO_3$ in soil profiles has been a more reliable property for comparing soil development for the Paradox Basin studies.

Both the morphology and the content of pedogenic carbonate in a soil column show progressive changes with time (Gile and Grossman, 1979; Bachman and Machette, 1977; Machette, 1978). Many investigators (Gardner, 1972; Lattman, 1973; Gile, 1975; Machette et al., 1976) have demonstrated that wind-blown dust is the principal source of pedogenic carbonate in areas of noncalcareous bedrock in the southwestern United States. The carbonate content of a soil therefore reflects the amount of time that the soil has been at or near the ground surface, assuming that the rate of carbonate influx, extent of leaching, and degree of soil erosion are relatively constant. Bachman and Machette (1977) and Shroba (1977) defined the sequential stages of carbonate morphology used in this study (Table 4-2). Morphological sequences of carbonate development for deposits of known age in different regions of the southwestern United States are shown on Figure 4-2.

The distribution of $CaCO_3$ within a soil profile depends on the texture of the parent material; therefore, visual comparisons of carbonate concentration or morphology may not accurately indicate how much pedogenic carbonate is present in the profile, or which profile has the greatest amount of carbonate. In order to obtain data that could be compared for soils developed in different parent materials, samples were collected throughout the soil profile, and a laboratory measurement of the amount of soil carbonate present in each sample was made. Those values were summed for each profile and expressed as the total mass of accumulated $CaCO_3$ present throughout each profile. This calculation considers the bulk density of the deposits and original carbonate content of the parent material.

Use of pedogenic properties to interpret soil ages in the Southwest is dependent on the soil moisture, temperature regimes, and carbonate influx rates. Soil classification by the Soil Conservation Service utilizes soil moisture and temperature data, whereas the key variable in calculating the age of a calcic soil is the rate at which carbonate dust falls on the ground surface and is accumulated in the soil profile.



A horizon	Zone where organic matter accumulates. A horizons are typically thin and light-colored because of sparse vegetation.
v	Vesicular structure common to desert soil.
B horizon	Zone where clay accumulates by translocation from overlying horizons and by weathering in place.
Cambic	B horizons showing only slight buildup of clay and reddening of parent material.
Argillic	B horizons (Bt) showing significant clay buildup and oriented clay films on grains or ped surface.
	In the field, B horizons commonly show blocky structure, which results from breaking of soil into peds during dehydration.
Cca horizon	Zone where translocated calcium carbonate accumulates. Present in all but very young desert soils.
K horizon	Cca horizon containing > 50% continuous calcium carbonate.
m	Cemented zone
Cox horizon	Zone that is more weathered than the underlying parent material but lacks the properties of A, B, or Cca horizons.
cs, sa	Accumulations of gypsum (cs) or salts (sa) in C horizon.
Cr horizon	Weathered bedrock underlying soil.

Source: Birkeland, 1984

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TYPICAL SOIL HORIZONS, SEMIARID AND ARID SOILS

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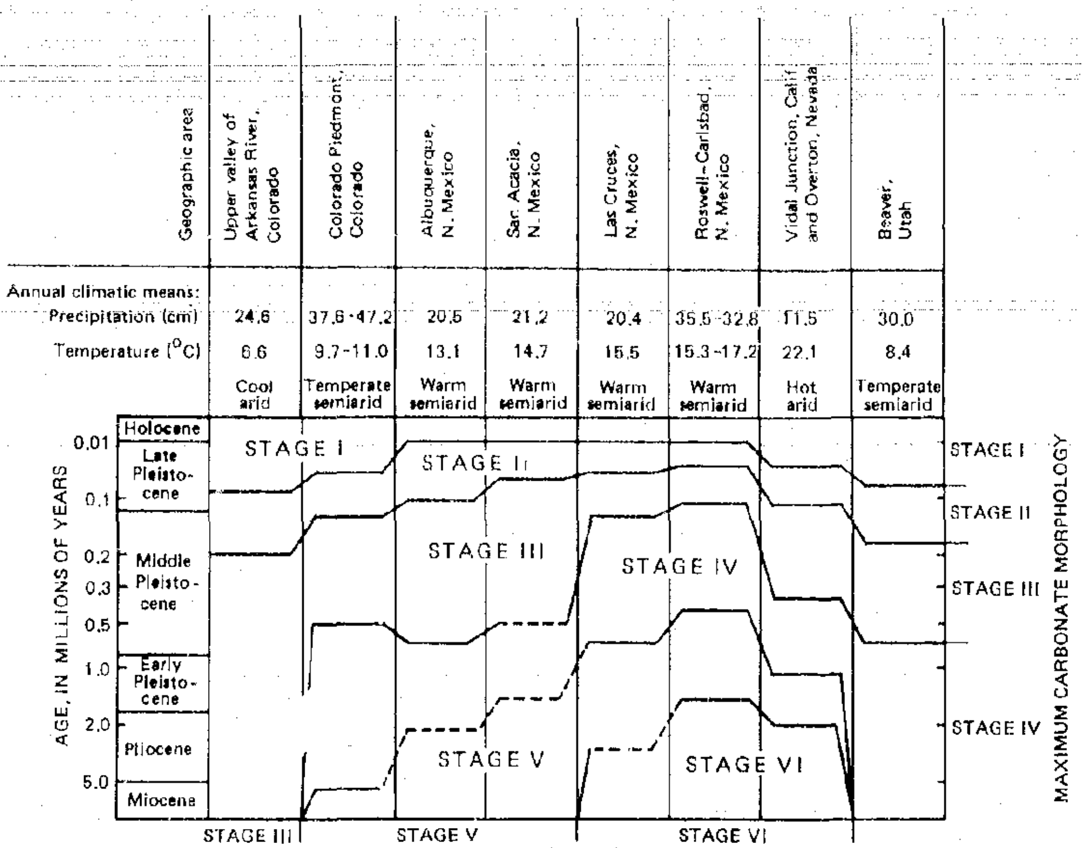
Figure 4-1

Table 4-2. Morphologic Stages of Carbonate Accumulation in Soils

Stage	Gravelly Parent Material	Nongravelly Parent Material
I	Sparse to common, thin, discontinuous coatings on clasts, usually on undersides	Sparse to common filaments in soil; flakes or coatings on sand grains or pad faces
II	Continuous, thin to thick coatings on tops and undersides of clasts; some interclast fillings; matrix somewhat whitened	Few to common nodules; nodules are soft, 0.5 cm to 4 cm (0.2 to 1.6 in) in diameter; matrix slightly whitened
III	Continuous interpebble fillings; cemented and plugged horizons in advanced form	Many coalesced nodules; matrix is moderately cemented
IV	Laminar horizon, <0.2 cm to 1 cm (0.07 to 0.4 in) thick, overlying plugged horizon. Cemented platy to weak tabular structure and indurated laminae. Km horizon is 0.5 to 1 m (1.5 to 3 ft) thick.	
V	Thick (>1 cm [0.4 in]) laminar horizon overlying plugged horizon; incipient brecciation and pisolite development. Indurated and dense, strong platy to tabular structure. Km horizon is 1 to 2 m (3 to 6 ft) thick.	
VI	Strong brecciation and pisolite development. Multiple generation of laminae, breccia, and pisolites; recemented. Indurated and dense, thick, strong, tabular structure. Km horizon is commonly >2 m (6 ft) thick.	

Sources: Bachman and Machette (1977); Shroba (1977); Machette (1985).



LEGEND:

STAGE I Morphological stage of calcic soil development; described in Table 4-2

Source: Machette, 1985

LOG 1598 REV. 1—4/4/86	STAGE AND AGE OF CARBONATE SOILS, SOUTHWESTERN UNITED STATES Quaternary Topical Report Project No. 17000 Woodward-Clyde Consultants	Figure 4–2

4.1.1.1 Soil Moisture and Temperature Conditions

The temperature and moisture regimes assigned to sites in southeastern Utah by the Soil Conservation Service have been used to classify soil series in the Canyonlands area (Soil Survey Staff, 1975, p. 412). Although temperature and moisture probes have not been installed in the Canyonlands area, soil conditions have been estimated from weather station records, site vegetation, periodic measurements, and soil morphology. Estimated annual precipitation at locations in the Paradox Basin where soil profile data have been collected by Woodward-Clyde Consultants (WCC) is presented in Table 4-3. A more detailed discussion of present and past climatic conditions is given in Chapter 2.0.

Table 4-3. Estimated Annual Precipitation at Study Sites in the Paradox Basin

Site	Average Annual Precipitation mm	Average Annual Precipitation in
Terraces west of Green River	150 - 200	6 - 8
Bartlett Wash	150 - 200	6 - 8
Spanish Valley terraces	200 - 305	8 - 12
Amasas Back, Spanish Valley	305 - 355	12 - 14
Indian Creek terraces, Gibson Dome	200 - 250	8 - 10
ER-1 drill site	250 - 305	10 - 12
Dry Wash, Elk Ridge Area	250 - 305	10 - 12
White Mesa eolian deposits	250 - 305	10 - 12
Gravel pediments, Blanding area	305 - 405	12 - 16
Gravel pediments, Monticello	305 - 405	12 - 16

Areas lower than approximately 1,524 m (5,000 ft) above mean sea level (MSL) in the Canyonlands region have a typical aridic moisture regime. The U.S. Department of Agriculture (Soil Survey Staff, 1975, pp. 51-57) classifies aridic soils as being dry (containing less than 15-bar water) for more than 180 days each year and never moist (containing more than 15-bar water) for as long as 90 consecutive days per year. Areas between approximately 1,524 to 2,225 m (5,000 to 7,300 ft) MSL have ustollic aridic moisture regimes. These areas are more moist than lower regions but less moist than those of the ustic regimes. Soil moisture conditions in areas from approximately 2,225 to 2,377 m (7,300 to 7,800 ft) MSL are classified as ustic. These soils are dry for 90 to 180 days each year, and remain moist for more than 90 consecutive days and/or for more than 180 cumulative days a year.

In all areas below at least 2,380 m (7,800 ft) MSL, precipitation and stored soil moisture together are less than summer evapotranspiration. Little or no leaching occurs in soils with aridic moisture regimes, as evidenced by the presence of soluble salts in the soil profiles. Limited leaching occurs in areas having ustic moisture regimes, but $CaCO_3$ can still accumulate in the soil profile. The thick and sometimes strongly cemented layers of carbonate accumulation observed in aridic landscapes are probably in relict landforms, and probably developed during a period when more soil water was available for both leaching of soluble salts from surface soil horizons and the concomitant accumulation of carbonate in subsoil horizons.

Most portions of southeastern Utah below approximately 2,286 m (7,500 ft) MSL possess a mesic temperature regime (Soil Survey Staff, 1975, p. 63). The mean annual soil temperature for this regime is defined as between 8 and 15°C (46 and 59°F), with summer and winter temperatures at 50 cm (20 in) depth differing by more than 5°C (9°F). Localized areas along the Colorado River canyon have soils with thermic temperature regimes, characterized by mean annual soil temperatures between 15 to 17°C (59 to 63°F), and summer and winter temperatures at 50 cm (20 in) depth differing by more than 5°C (9°F) (Lammers, 1983).

4.1.1.2 Carbonate Influx

Eolian dust and dissolved calcium in rainwater are probably the major suppliers of $CaCO_3$ to soil profiles in the southwestern United States (Gile and Grossman, 1979; Machette, 1985). The rate of calcic soil development is therefore dependent on the long-term influx rate of airborne $CaCO_3$, which is in turn dependent on wind and precipitation. The extent of exposed calcareous deposits, such as lake beds or limestone bedrock, also influences the amount of airborne $CaCO_3$ deposited in downwind areas. Present carbonate influx rates, which are probably greater than long-term Quaternary influx rates (Machette, 1985), can provide a relative index of carbonate influx rates in different areas.

No data concerning modern $CaCO_3$ influx are available for southeastern Utah, but influx data are available for areas in New Mexico and for the Beaver area of southwestern Utah (Figure 4-2). Modern dust fall in the vicinity of Las Cruces, New Mexico contributes 0.02 to 0.04 g/cm^2 of $CaCO_3$ per 1,000 years to the soil column (Gile and Grossman, 1979,; Machette, 1985). The mean annual precipitation of 200 mm (8 in) in that region contains sufficient dissolved calcium to accumulate 0.15 to 0.2 g/cm^2 of $CaCO_3$ in the soil column per 1,000 years. These measured amounts of dissolved calcium concentrations in rainwater may be similar to those of southeastern Utah (Junge and Werby, 1958, Figure 7); however, local sources of calcareous dust may be more abundant in the Las Cruces area (Machette, 1985).

The rate at which carbonate accumulates in a soil profile is controlled by the rate at which calcium ions (Ca^{++}) are supplied to the ground surface, and by the amount of rainfall available to move these ions down into the soil. If rainfall is too great relative to the Ca^{++} supply, $CaCO_3$ is leached from the soil. Based on present data, climatic conditions in the Paradox Basin are most similar to the Albuquerque and San Acacia study areas of Machette (1985; Figure 4-2). Carbonate accumulation rates in southeastern Utah would thus be expected to be similar to those areas and less rapid than those in the Roswell, New Mexico area, where limestone-rich alluvium provides an additional source of $CaCO_3$. However, because rainwater in southeastern Utah may be more enriched in calcium than in the Albuquerque area (Junge and Werby, 1958), accumulation rates could be more rapid in the Paradox Basin. Soils in the vicinity of Monticello, which has a higher rainfall than topographically lower parts of the study region, have climatic conditions most similar to the Beaver study area of Machette (1985, Table 2).

4.1.1.3 Sampling and Laboratory Procedures

The procedures for field sampling of soil profiles and laboratory analysis of soil properties are described in WCC (1982b; 1982c) and summarized below. The soil exposure of interest is described in the field, and samples are collected for laboratory analyses. Particle size data are derived by wet-sand sieving a sample split, and by hydrometer analysis. The moisture factor and bulk density values are also measured for all samples from profiles for which $CaCO_3$ content is to be calculated. Carbonate content of fine-grained samples is determined with a calcimeter; an acid neutralization method is used for coarse-grained samples.

Pretreatments were applied to a limited number of samples in the initial phase of laboratory analysis to assess the necessity of removing organic material and manganese oxide, silica cement, iron oxides, and $CaCO_3$ prior to the particle size analysis. The results of these tests indicated that only $CaCO_3$ had any significant aggregatory effect, even after dispersion; therefore, all samples were subsequently pretreated to remove $CaCO_3$ prior to particle size analyses.

4.1.1.4 Results

The apparent usefulness of calcic soil development for age assessments was demonstrated in an early phase of the study, during which carbonate content in a multiple series of stream terraces in Spanish Valley, south of Moab, was measured. The soil carbonate data provided dates that were acceptably correlative with the hypothesized age of the deposits, as established by the glacial chronology developed by Richmond (1962) in the nearby La Sal Mountains (WCC, 1982a, Vol. I, pp. 3-11 to 3-16).

A total of 35 soil profiles were sampled and described in the Paradox Basin in Utah for the Quaternary studies. The accumulation of $CaCO_3$ was calculated for all profiles (Table 4-4), and particle size analyses were completed for 23 of these sites (Table 1-1). The laboratory analyses were conducted by Nelson Laboratories, Stockton, California.

The locations where soil carbonate has been measured are shown on Figure 1-1. Interpretation of the laboratory soils data for Spanish Valley,

Table 4-4. Soil Carbonate Data
(Page 1 of 3)

Locality	Location	Deposit	Est. Total Ped. $CaCO_3$ (g/cm^3)	Est. Age[(a)] (x1,000 years)
3	T25S, R16E, Sec. 11-1	Alluvial gravel Green River terrace	102	400 - 680
6	T26S, R22E, Sec. 7-1	Alluvial gravel Placer Creek	61	245 - 405
7	R26S, R22E, Sec. 22-1	Eolian deposit Gold Basin	1.8	7 - 12
12	T27S, R16E, Sec. 8-1	Eolian deposit Antelope Valley	111 (average)	~730
14	T27S, R23E, Sec. 5-2	Alluvial gravel Older Harpole Mesa	182	~730
15	T27S, R23E, Sec. 16-1	Alluvial gravel Younger Placer Creek	37	150 - 245
16	T27S, R23E, Sec. 17-1	Alluvial gravel Younger Beaver Basin	9	35 - 60
17	T27S, R23E, Sec. 18-1	Alluvial gravel Older Placer Creek	36	145 - 240
18	T27S, R23E, Sec. 18-2	Alluvial gravel Older Beaver Basin	7	30 - 45
19	T27S, R23E, Sec. 20-1	Alluvial gravel Older Placer Creek	38	150 - 255
20	T27S, R23E, Sec. 22-1	Alluvial gravel Middle Harpole Mesa	29	115 - 195
21	T27S, R23E, Sec. 28-1	Alluvial gravel Middle Harpole Mesa	41	165 - 275
32	T30S, R21E, Sec. 16-7	Alluvial gravel Indian Creek, 8-m terrace	16	65 - 105
33	T30S, R21E, Sec. 16-8	Alluvial gravel Indian Creek, 10-m terrace	7	30 - 45
34	T30S, R21E, Sec. 16-6	Alluvial gravel Indian Creek, 10-m terrace	9	35 - 60

Table 4-4. Soil Carbonate Data
(Page 2 of 3)

Locality	Location	Deposit	Est. Total Ped. $CaCO_3$ (g/cm^3)	Est. Age[a] (x1,000 years)
35	T30S, R21E, Sec. 16-5	Alluvial gravel Indian Creek, 12-m terrace	31	125 - 205
36	T30S, R21E, Sec. 16-4	Alluvial gravel Indian Creek, 12-m terrace	10	40 - 65
37	T30S, R21E, Sec. 16-3	Alluvial gravel Indian Creek, 20-m terrace	15	60 - 100
38	T30S, R21E, Sec. 16-2	Alluvial gravel Indian Creek, 20-m terrace	11	45 - 75
39	T30S, R21E, Sec. 16-1	Alluvial gravel Indian Creek, 32-m terrace	30	120 - 200
40	T31S, R18E, Sec. 9-1	Eolian deposit The Grabens	29	115 - 195
41	T31S, R18E, Sec. 11-1	Fine-grained alluvium The Grabens	17	70 - 115
46	T31S, R21E Sec. 11-1	Eolian deposit The Island	1.6	6 - 11
50	T33S, R24E, Sec. 32-1	Alluvial gravel Monticello gravel pit	117	470 - 780
55	T36S, R22E, Sec. 24-1	Alluvial gravel Blanding gravel pit	220	800 - 1,465 (>730)
57, 62 (combined)	T37S, R19E, Sec. 30-1,6	Eolian deposit ER-1 Site	18	70 - 120
58	T37S, R19E, Sec. 30-2	Eolian deposit ER-1 Site	14	55 - 95
59	T37S, R19E, Sec. 30-3	Eolian deposit ER-1 Site	(b)	(b)
60	T37S, R19E, Sec. 30-4	Eolian deposit ER-1 Site	(b)	(b)
61	T37S, R19E, Sec. 30-5	Eolian deposit ER-1 Site	(b)	(b)

Table 4-4. Soil Carbonate Data
(Page 3 of 3)

Locality	Location	Deposit	Est. Total Ped. $CaCO_3$ (g/cm^3)	Est. Age[a] (x1,000 years)
66	T37S, R20E, Sec. 31-1	Eolian deposit Dry Wash	29	115 - 195
71	T37S, R22E, Sec. 32-1	Eolian deposit White Mesa	14	55 - 95
72	37S, R22E, Sec. 33-1	Eolian deposit White Mesa	84	335 - 560
82	T39S, R21E, Sec. 24-1	Eolian deposit No Man's Island	193	770 - 1,285

(a) Age estimate based on a carbonate accumulation rate of 0.15 to 0.25 g/cm^2/1,000 years. Deposits with an estimated age of more than 730,000 years have reversed paleomagnetic signatures.

(b) No significant pedogenic carbonate has accumulated in these profiles.

an area west of the Green River, and the Gibson Dome study area was reported by WCC (1982a, Vols. I, II, and V). Since publication of the 1982 report, laboratory data have been received for seven additional soil profiles developed in eolian deposits in the Elk Ridge area and on White Mesa near Blanding, from three sites in gravel deposits derived from the Abajo Mountains, from one gravel site in Spanish Valley, and from two soil profiles described in the Grabens area. The pedogenic carbonate content in gravel terraces in the Gibson Dome area was also recalculated. These new and recalculated laboratory results are presented in Section 4.2. Soil data from the Grabens area are discussed in Section 3.2. The remaining sites are discussed in Section 4.2.

To be useful as a dating technique, the rate of carbonate influx into an area needs to be determined. Approximations of these rates can be derived by measuring the soil carbonate accumulated in deposits for which age control is available. The emphasis in the Paradox Basin study has been on determining long-term rates (Section 4.1.1.4.1). More recently, Machette (1985) has recognized the apparent variability between long-term and Holocene rates (Section 4.1.1.4.2).

4.1.1.4.1 Long-Term Carbonate Accumulation Rate. Deposits with reversed paleomagnetic polarity were used to calculate a maximum long-term carbonate accumulation rate for southeastern Utah (Table 4-5). These rates are

Table 4-5. Accumulation Rates of Calcium Carbonate in Early Pleistocene Soils and/or Paleomagnetically Reversed Deposits in the Paradox Basin Area

Locality[a]	Site	Elevation m (ft)	Ht. Above Stream Level m (ft)	Total $CaCO_3$ in <2mm Fraction[b] (g/cm^2)	Estimated $CaCO_3$ Content of Parent Material ≤ 2mm fraction %; g/cm^2	Total $CaCO_3$ in >2mm fraction (g/cm^2)	Estimated $CaCO_3$ Content of Parent Material[c] >2mm fraction %; (g/cm^2)	Total $CaCO_3$ (g/cm^2)	Estimated Total Pedogenic $CaCO_3$[c] (g/cm^2)	Polarity[e]	Max $CaCO_3$ Accumulation Rate g/cm^2/1000 yr
3	Sec. 11, T25S, R16E C...n River terrace	1,490 (4,900)	270 (880)	61	10; 15[f]	70	10; 14	131	102	--	0.14
4, 5	Sec. 14, T26S, R15E Keg Knoll	1,615 (5,300)	330 (1,080)	--	--	--	--	--	--	R(?)	--
12	Sec. 8, T27S, R15E Antelope Valley[f]	1,615 (5,300)	380 (1,240)	144	2; 16 8; 51	--	--	144	125 93	(?)	0.15
9, 14	Sec. 5, T27S, R23E Johnson's-Up-On-Top	1,770 (5,800)	255 (840)	95	5; 11[g]	114	3.5; 16	209	182	R	0.25
50	Sec. 32, T33S, R24E Monticello gravel pit	2,090 (6,850)	365 (1,200)	112	1; 7	28	3.3; 16	140	117	--	0.15
55	Sec. 24, T36S, R22E Blanding gravel pit	1,920 (6,300)	275 (900)	167	2; 11	99	7.5; 35	267	220	R	0.30
72	Sec. 33, T37S, R22E White Mesa	1,705 (5,600)	195 (640)	98	1, 3.5[g]; 14	--	--	98	84	--	0.12
92	Sec. 24, T39S, R21E No Man's Island	1,540 (5,060)	150 (500)	230	8.4; 40	4	11.5; 1	234	193	--	0.26

(a) Localities are shown on Figure 1-1 and listed on Table 1-1.
(b) The total mass of $CaCO_3$ expressed in grams of $CaCO_3$ per square centimeter of soil area is computed by summing the $CaCO_3$ mass in each horizon or sampling interval. Carbonate content (weight percentage, measured in laboratory analysis) is multiplied by bulk density (g/cm^3) of each horizon and the horizon thickness (cm) to obtain the $CaCO_3$ mass in each horizon (expressed as g/cm^2 of soil column). Bulk densities of fine-grained material were measured by a water-volume-displacement technique using wax-coated soil clods. The original $CaCO_3$ content of the parent material, estimated from the $CaCO_3$ content at the base of the soil profile or nearby equivalent parent material, was calculated for the soil column and subtracted from the total calculated $CaCO_3$.
(c) Estimates based on laboratory analysis for the whole soil profile.
(d) $CaCO_3$ content for horizons not analyzed were estimated from $CaCO_3$ content of adjacent horizons.
(e) Magnetic polarity was not measured where no data given. R = reversed; (?) = questionable.
(f) Two different estimates used for $CaCO_3$ content of parent material.
(g) Parent material for lower soils appears to be more calcareous than upper parent material. See Table 4-24.

considered to be maximum because the exact ages of the deposits are not known; however, they are at least 730,000 years old,* which represents the end of the reversed Matuyama paleomagnetic epoch (Mankinen and Dalrymple, 1979). A maximum rate of 0.25 $g/cm^2/1,000$ years was calculated for the Spanish Valley area near Moab (Locality 14); 0.15 $g/cm^2/1,000$ years for the Green River area west of Moab (Locality 12), (WCC, 1982a, Vol. I, p. 3-16); and 0.30 $g/cm^2/1,000$ years for the gravel deposits near Blanding (Locality 55) (Section 4.2.3.2).

Deposits considered to be correlative on the basis of their topographic or geomorphic setting, or their calcic soil development, but where no paleomagnetic studies were done, have yielded maximum $CaCO_3$ accumulation rates of 0.12 $g/cm^2/1,000$ years (White Mesa near Blanding, Locality 72); 0.14 $g/cm^2/1,000$ years (Green River terrace, Locality 3); and 0.26 $g/cm^2/1,000$ years (No Man's Island, southwest of Blanding, Locality 82) (Table 4-5). Soil profiles at all of these sites demonstrate the well-developed (sometimes multiple) calcic soils that are characteristic of early Pleistocene deposits. Although these calculated maximum influx rates assume an age of 730,000 years for the paleomagnetically reversed or correlative deposits, it is very likely that the deposits are much older, as indicated by their high topographic positions above present stream levels. The reversed polarity measured in the deposits may represent the Gilbert reversed epoch, which lasted from 5.1 to 3.3 million years ago (Mankinen and Dalrymple, 1979). However, for the purposes of Paradox Basin Quaternary studies, the younger reversed age is assumed in order to provide the maximum conservatism in calculating the rates at which geomorphic processes have been occurring during Quaternary time.

At Fisher Valley, 29 km (18 mi) east of Moab, carbonate influx rates calculated by the U.S. Geological Survey (USGS) represent the best data available for southeastern Utah because of the age control on the measured sequence. At this location, a carbonate accumulation rate of 0.15 $g/cm^2/1,000$ years was calculated for the Quaternary sequences that overlie two datums: the Lava Creek Ash, with an assumed age of 610,000 years before present (BP) (Izelt, 1981); and the Bruhnes-Matuyama paleomagnetic reversal, dated at 730,000 years BP (Colman, 1983). Several unconformities occur within the sequence; therefore, the actual long-term accumulation rate may be somewhat higher because the exposure may not represent a full depositional sequence.

The Fisher Valley carbonate accumulation rates are equivalent to the lower rates calculated for this project (Table 4-5). Because the variations caused by climatic conditions, erosion, or the age of the deposit cannot be differentiated with the present data, age estimates reported herein using soil carbonate data are expressed as a range. Considering the calculated influx rates discussed above and presented in Table 4-5, an estimated carbonate

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* Maximum carbonate influx rates of 0.16 to 0.26 $g/cm^2/1,000$ years reported by WCC (1982a, Vols. I and II) were based on the assumption that the last paleomagnetically reversed epoch ended 700,000 years ago. In this report, the end of the Matuyama reversed epoch is assumed to be 730,000 years ago (Mankinen and Dalrymple, 1979). As a result, the calculated maximum carbonate influx rate decreases to 0.15 to 0.25 $g/cm^2/1,000$ years.

influx rate ranging from 0.15 to 0.25 g/cm/1,000 years has been used in this report for calculating the age of deposits exhibiting calcic soil development. Application of the Fisher Valley data to the age calculations would result in the older of the age estimates reported herein.

4.1.1.4.2 Holocene Carbonate Accumulation Rates. Workers in the Las Cruces, New Mexico, area of the Southwest have reported that carbonate accumulation rates computed for Holocene and latest Pleistocene (<18,000-year-old) soils are higher than rates computed for soils on older deposits (Machette, 1985). Data that they derived from seven Holocene soils yield a mean accumulation rate of 0.46 g/cm^2/1,000 years; the pedogenic carbonate accumulation rate in five latest Pleistocene soils is 0.43 g/cm^2/1,000 years. Their data for older soils (pre-latest Pleistocene to early Pleistocene) indicate mean accumulation rates of 0.21 to 0.29 g/cm^2/1,000 years, i.e., approximately one-half to two-thirds of the younger rates.

During this Paradox Basin study, one late-Holocene rate of 1.39 g/cm^2/1,000 years was calculated at Locality 7 in Spanish Valley by using a radiocarbon date of 1,280$\pm$55 years BP as a control (WCC, 1982a, Vol. I, p. 3-12). This accumulation rate is higher than the Las Cruces data for young deposits. A much higher rate of 3.84 g/cm^2/1,000 years was derived from eolian deposits overlying a charcoal layer dated at 430$\pm$110 years BP at Locality 46.

Machette (1985) related the large apparent temporal variation in carbonate accumulation rates to climatic control. Machette's model called for long (120,000-year) intervals of low carbonate accumulation (approximately 0.25 g/cm^2/1,000 years) during pluvial conditions, interrupted by short (10,000-year) intervals of high $CaCO_3$ accumulation (0.5 g/cm^2/1,000 years) during interpluvial climates. The high Holocene accumulation rates are interpreted to be a function of the present interpluvial stage.

4.1.1.4.3 Composite Rates. Discussion of the estimated ages of deposits based on pedogenic character in previous WCC reports was based on a calculated long-term influx rate of 0.16 to 0.26 g/cm^2/1,000 years (WCC, 1982a, Vols. I, II, and V). In this report, a long-term influx rate of 0.15 to 0.25 g/cm^2/1,000 years is used (see footnote in Section 4.1.1.4.1). In some of the discussions in this report, however, the possibility of a higher influx rate during Holocene time has been considered in the age calculation (Section 3.2.2.1). If the influx rate of the last 18,000 years is assumed to be 0.47 g/cm^2/1,000 years instead of 0.15 to 0.25 g/cm^2/1,000 years, the composite age calculation reduces the estimated age range of deposits by 14,000 to 36,000 years.

4.1.1.5 Means to Assess Accuracy of Results

The evaluation of the accuracy of age estimates based on soil carbonate accumulation rates has been difficult because of the lack of other dating techniques that are applicable to the derived age ranges shown in Table 4.4. The qualitative methods that have been most commonly applied are stratigraphic/geomorphic reasonableness, topographic and geologic setting, and, for the older deposits, paleomagnetic polarity. Of the quantitative dating methods that could potentially be used to evaluate the calcic soil ages, radiocarbon dating and amino acid analysis are useful for evaluating soil carbonate ages derived from young (<35,000-year-old) deposits; uranium-series (U-series) and TL dating can be used for deposits up to approximately 150,000 years old (and potentially older). Although ^{14}C dating is considered the most accurate of the evaluation methods, almost all of the radiocarbon materials collected thus far on this project are less than 10,000 years old, and the calcic soils of interest have formed on deposits that range in estimated age from 10,000 to >1 million years. In the Paradox Basin study, only TL analyses have been used to quantitatively assess the derived calcic soil ages. However, because of the newness of this dating method (Section 4.1.3), accuracy assessments based only on the comparison of soil data with TL dates remain open to question. Comparison of the calcic soil data and the TL dates for specific areas is presented in Section 4.1.3.

4.1.1.6 Reproducibility of Results

The reproducibility of laboratory results was evaluated to assess the reliability of the derived data, particularly for crucial samples, and to satisfy quality assurance requirements. Reproducibility can be verified by (1) submitting disguised duplicate samples to a laboratory, or (2) sending splits of a sample to two or more facilities. For the pedologic studies, one disguised duplicate sample was submitted for every 12 samples sent to the laboratory for both particle size analysis and $CaCO_3$ measurements. Additionally, the laboratory arbitrarily reran one sample for approximately every 15 samples when measuring $CaCO_3$ content.

Values obtained for 22 samples rerun by the laboratory in the acid neutralization analyses were all reproduced within 12 percent; 72 percent of the data were reproduced within 5 percent. Values obtained for the five disguised duplicate samples were less reproducible. The result for one of the five samples was reproduced within 5 percent; reproduced values for the others varied from 20 to 60 percent from the original value. The reason for these discrepancies is not readily apparent. The carbonate content of the disguised duplicates is comparable to that of most laboratory-duplicated samples, and therefore should not have been a factor. There is no indication that the laboratory made multiple runs on their selected duplicates to obtain two closely similar values. In general, reproducibility in both evaluations decreased with a decrease in carbonate content of a sample.

In the calcimeter analyses, 81 percent of the results from 47 samples rerun by the laboratory were reproduced within 5 percent of the original value, and 91 percent of the values were reproduced within 10 percent. Of the 24 disguised samples, 80 percent were also duplicated within 5 percent. For samples containing less than 1.5 percent carbonate, the second value varied from the first by as much as 30 percent. For the 21 samples containing more than 1.4 percent $CaCO_3$, 90 percent of the carbonate values were duplicated within 5 percent.

4.1.2 Carbon-14

The ^{14}C radioactive isotope is produced in the Earth's upper atmosphere during the bombardment of nitrogen-14 by neutrons produced by cosmic rays. The ^{14}C atoms are incorporated into carbon dioxide molecules, which in turn mix throughout the hydrosphere and atmosphere. A steady-state equilibrium is maintained between the radioactive and nonradioactive carbon atoms, and ^{14}C is continuously absorbed by plants and animals while they are alive. When the organism dies the absorption stops, and the activity of ^{14}C begins to decline through radioactive decay.

In conventional radiocarbon dating techniques, a date is derived by measuring the radioactivity of the sample. This technique assumes that the production of ^{14}C is constant, as is the global $^{12}C/^{14}C$ ratio, and that when the organism dies, ^{14}C is not preferentially added or removed. In actuality, the radiocarbon content of the atmosphere has varied through time and can be affected by fluctuations in the Earth's magnetic field, the burning of fossil fuels, testing of atomic bombs, and the operation of nuclear reactors. Corrections have been calculated for the last 8,000 years, for which the dendrochronologic record is available; however, variations that occurred before 8,000 years ago are much more difficult to measure, both in terms of duration and magnitude (Faure, 1977).

Despite these potential problems, the ^{14}C dating method is considered to be a reliable measure of time for the last 35,000 to 40,000 years, and is widely accepted in the geologic community. Through careful construction, use, and insulation of a laboratory facility; or by the use of a cyclotron or a tandem accelerator to directly count ^{14}C atoms, the upper limit for reliable dates has been extended to 70,000 years.

4.1.2.1 Sampling Procedures

Materials collected for ^{14}C dating during this project include charcoal, charcoal disseminated in soil, land snail shells, and a mammoth tusk. Care was taken not to handle the samples with bare hands; the material was removed from the natural setting with a trowel or metal knife and placed directly in new aluminum foil. If the sample was moist, it was dried prior to storage or shipping to prevent formation of mold.

A sample submitted for dating by conventional ^{14}C techniques should consist of at least a cupful (approximately 240 cm^3) of charcoal in order to obtain sufficient carbon after burning, and to provide an accurate date with small standard deviations. The primary advantage of new ^{14}C methods, which use an accelerator or a cyclotron, is that samples of very small size (approximately 15 mg [approximately 30 cm^3 or half a teaspoonful]) can be dated. Because a cyclotron or accelerator dating facility was not available on a commercial basis at the time when Paradox field studies were in progress, the radiocarbon dating was done by conventional techniques.

4.1.2.2 Laboratory Procedures

A total of 41 samples collected for radiocarbon dating were of sufficient size to be conventionally dated. These were analyzed by the Dicarb

Radioisotope Company, Norman, Oklahoma, and by Beta Analytical, Incorporated, Coral Gables, Florida, using the liquid scintillation method. One additional sample was dated at the University of Arizona, Tucson, to assess the accuracy of a date previously obtained from another facility. In a liquid scintillation process, the sample is burned and the carbon dioxide that is given off is converted to liquid benzene. The activity of the radiocarbon in the gas is then counted in a liquid scintillation spectrometer.

Twenty-five additional samples that were too small in size to be dated at the facilities described were submitted to the Radiocarbon Dating Laboratory at Washington State University in Pullman, Washington. This laboratory has a scaled-down version of the ^{14}C counting tubes commonly used and can date samples that contain as little as 30 mg (0.001 oz) of carbon. They convert the carbon dioxide to methane rather than benzene and shelve the sample for sufficient time to remove the possible contaminating effect of radon. The activity is then counted on a methane gas proportional counting tube.

Dates for two of the small samples were calculated using the barium hydroxide process. In this process, the sample is pretreated as per the more conventional methods, and then combusted in a furnace that has an oxygen-enriched atmosphere. The gas is passed through potassium permanganate and into a bottle containing a known amount of barium hydroxide, where the carbon dioxide gas reacts with the barium hydroxide to form a barium carbonate precipitate. The precipitate is filtered off, dried, and weighed, and the weight of carbon calculated. Carbon dioxide gas is released again by reacting the barium carbonate with phosphoric acid, and is counted in a detector diluted up to pressure. The age of the sample is calculated based on the weight of carbon in the sample and the disintegrations per minute of the sample gas.

4.1.2.3 Means to Assess Accuracy of Results

The accuracy of the radiocarbon dates can be evaluated by (1) comparing dates obtained from a stratigraphic sequence at one locality, (2) comparing ages of units known to be correlative, (3) comparing the dates with data derived by other dating techniques, and (4) running duplicate analyses on samples. The accuracy of ^{14}C dates derived from debris collected from pack rat middens is assessed by comparing plant assemblages found in the dated midden with those reported elsewhere in the area for that time period. The stratigraphic details for radiocarbon samples are presented in Table 1-1. They are discussed in Chapters 2.0 and 3.0 for the Canyonlands and the Needles Fault zone, respectively, and are addressed in Section 4.2 for other locations in the Paradox Basin study area.

4.1.2.4 Results

Because of its acceptance by the scientific community, radiocarbon dating was used to calibrate and evaluate other dating processes whenever possible in the Paradox Basin study. For example, radiocarbon data were used to verify paleotemperature assumptions in the amino acid analyses of snail shells (Section 4.1.4), and TL samples were collected at several localities where ^{14}C

dates were available to evaluate the accuracy of the derived TL dates. However, the reliability of the derived radiocarbon dates was still evaluated to the extent possible with the approach given in Section 4.1.2.3. Where the radiocarbon data were assessed to be stratigraphically unreasonable, and other chronologic data appeared more accurate for a particular setting, ^{14}C data were judged to be in error.

The radiocarbon data include 46 dates derived for geologic deposits and 21 dates derived for material collected from pack rat middens (Table 4-6). Most of the geologic dates were derived from charcoal collected from fine-grained alluvial and eolian deposits; a few samples consisted of organic flood debris, wood, land snail shells, and tusk material. Of these materials, the organic flood debris is likely to yield the most accurate dates because such material has probably not been reworked from an older deposit, the sample is commonly of sufficient size preferred for laboratory analysis, and it represents a unique instant in time.

The dates derived from geologic deposits were all less than 13,000 years BP, and agree with the Holocene to latest Pleistocene age estimated for the deposits on the basis of their sedimentologic character and lack of soil development. Most of the ^{14}C dates represent single samples collected from an exposure; where more than one sample was collected, the dates are usually stratigraphically consistent. Individual exposures on Salt Creek (Section 2.5) and in the Grabens (Section 3.2) were the most heavily sampled; up to eight ^{14}C and TL samples were collected at any one location (Figures 2-6 and 3-11). These dates are all less than 5,000 years BP. Dates that do not fit into the chronologic sequence provided by the bulk of the ^{14}C data may represent carbonaceous material reworked from older fluvial deposits, if the date is too old; or may represent the remains of a charred root if the date is too young. Alternatively, analytical error could have been introduced by the small size of many of the samples (Table 4-6).

The pack rat middens yielded needles, branches, twigs, buds, seeds, and pack rat dung pellets for dates that ranged from 1,820 to 12,770 years BP. With one exception, all the radiocarbon dates derived from the pack rat middens were assessed to be reasonable. Two samples from Midden 8 at Allen Canyon Cave (Locality 52) (Table 4-6) were run because the subalpine plant assemblage found in the midden had not been reported elsewhere in the Southwest in middens as young as 7,500 years BP. The second derived date of 10,140 years BP fit the regional paleoecological scenario, and was judged to be the more accurate of the two (Betancourt and Biggar, 1985).

4.1.2.5 Reproducibility of Results

The reproducibility of ^{14}C dates derived during this project was assessed by submitting disguised duplicates to the laboratory doing the analyses for those particular samples, and by sending splits of a sample to one or more additional facilities. Sufficient material was collected at six sites for d. l'cate or triplicate samples (Table 4-7). From Locality 52, a second pack r midden sample, having a different composition from that of the first dated sample, was submitted to a second laboratory to check the date received from the first facility.

Table 4-6. Radiocarbon Dates Obtained From Quaternary Deposits, Paradox Basin
(Page 1 of 4)

Locality[a]	Site	Carbon-14 Date (yr BP)[b]	Lab No.[c]	Comments[d]
2	Sec. 23, T24S, R19E-2 Bartlett Wash	12,880 ± 370	BETA-2829	Fossil ivory [mammoth (?) tusk]. Very small sample size produced a larger-than-usual statistical error.
		>35,000 (?)	DIC-2065	Fossil ivory. Sample consisted of tusk section closest to head of animal.
7	Sec. 22, T26S, R22E-1 Spanish Valley	1,280 ± 55	DIC-1544	Charcoal, from Gold Basin Formation.
26	Sec. 17, T30S, R20E-1 Salt Creek[e]	310 ± 60	WSU-2776	Vegetal flood debris.
		102% Modern	WSU-2754	Charcoal. Sample split for triplicate dates.
		no date	DIC-2657	"No carbon." Duplicate of WSU-2754.
		no date	BETA	"No carbon." Duplicate of WSU-2754.
		1,735 ± 200	WSU-2798	Charcoal.
27	Sec. 17, T30S, R20E-2 Salt Creek[e]	3,360 ± 190[f]	WSU-2805	Charcoal.
		2,080 ± 200[g]	WSU-2774	Charcoal.
		2,920 ± 220	WSU-2808	Charcoal
		2,530 ± 210	WSU-2807	Charcoal.
		1,460 ± 250	WSU-2804	Charcoal.
		2,500 ± 210	WSU-2806	Charcoal.
		1,710 ± 260	WSU-2809	Root.
		1,790 ± 70	WSU-2810	Duplicate of WSU-2809.
28	Sec. 29, T30S, R20E-1 Salt Creek[e]	4,510 ± 600	WSU-2777	Charcoal.
29	Sec. 32, T30S, R20E-2 Salt Creek[e]	580 ± 150	DIC-2642	Charcoal from burn horizon. Split for triplicate dates.
		1,690 ± 230	BETA-6220	Duplicate of DIC-2642.
		2,585 ± 55	WSU-2755	Duplicate of DIC-2642.
		2,430 ± 70	WSU-2801	Charcoal.
		120% Modern[i]	WSU-2802	Charcoal.
		4,830 ± 640	WSU-2800	Charcoal with sand.
		1,640 ± 210	WSU-2799	Charcoal.

Table 4-6. Radiocarbon Dates Obtained From Quaternary Deposits, Paradox Basin
(Page 2 of 4)

Locality[a]	Site	Carbon-14 Date (yr BP)[b]	Lab No.[c]	Comments[d]
30	Sec. 1, T30S, R21E-3 Lower Harts Draw	7,760 ± 155	DIC-2062	Charcoal from burn layer.
31	Sec. 8, T30S, R21E-1 Indian Creek	Modern	DIC-1546	Charcoal from burn layer.
41	Sec. 11, T31S, R18E-1 The Grabens[h]	103% Modern 2,760 ± 200[g]	WSU-2796 WSU-2767	Organic debris; primarily chenopod seeds. Charcoal.
42	Sec. 11, T31S, R18E-2 The Grabens[h]	2,450 ± 210	WSU-2797	Charcoal.
44	Sec. 14, T31S, R18E-2 The Grabens[h]	300 ± 65 3,910 ± 690 110% Modern 2,700 ± 220	WSU-2766 WSU-2764 WSU-2763 WSU-2765	Organic debris. Charcoal. Wood (sagebrush). Charcoal.
45	Sec. 28, T31S, R18E-1 Cross Canyon, The Grabens[h]	102% Modern 6,420 ± 730[f] 1,020 ± 520 No date.	WSU-2795 WSU-2794 WSU-2768 WSU-2769	Wood Charcoal. Charcoal. "No Carbon."
46	Sec. 11, T31S, R21E-1 The Island	430 ± 110	DIC-1893	Charcoal layer from eolian deposits on top of 45 m (150 ft) gravel terrace.
47	Sec. 10, T32S, R21E-1,2 Cottonwood Creek	720 ± 550 1,270 ± 100 1,600 ± 100	DIC-1495 DIC-1547 DIC-1493	Charcoal, indicator age only; extremely small sample. Date is not considered reliable. Charcoal. Charcoal.
48	Sec. 7, T32S, R23E-1 Hart's Draw	5,160 ± 55	DIC-1548	Charcoal.

Table 4-6. Radiocarbon Dates Obtained From Quaternary Deposits, Paradox Basin
(Page 3 of 4)

Locality[a]	Site		Carbon-14 Date (yr BP)[b]	Lab No.[c]	Comments[d]
52	Sec. 27, T34S, R21E-1	(#1)	10,030 ± 300	BETA-5760	Douglas fir needles, twigs, and buds.
	Allen Canyon Cave	(#1)	9,660 ± 140	BETA-5589	Douglas fir wood.
	Pack rat middens[i]		10,030 ± 100	DIC-2598	Duplicate of BETA-5589.
		(#2)	7,200 ± 90	BETA-5586	Pack rat pellets.
		(#4)	1,820 ± 50	BETA-5766	Pack rat pellets.
		(#5)	3,000 ± 70	BETA-5585	Pack rat pellets.
		(#6)	3,400 ± 60	BETA-5583	Pack rat pellets.
		(#7)	11,310 ± 200	BETA-5756	Limber pine needles.
		(#8)	7,530 ± 200	BETA-5588	Douglas fir needles, twigs, and buds.
			10,140 ± 190	A-3120	Pack rat pellets.
		(#9)	10,070 ± 70	BETA-5767	Pack rat pellets.
56	Sec. 36, T37S, R18E-1 Kane Gulch		8,100 ± 345	DIC-2064	Charcoal.
63	Sec. 11, T37S, R20E-3 Comb Wash		12,500 ± 160[j]	BETA-4413	Snail shells.
64	Sec. 24, T37S, R20E-1 Comb Wash		410 ± 60	BETA-4416	Charcoal.
67	Sec. 31, T37S, R20E-3		2,380 ± 90	BETA-4415	Charcoal.
	Dry Wash		9,490 ± 90	BETA-4414	Charcoal disseminated in soil.
			7,840 ± 700	BETA-6221	Duplicate of BETA-4414.
			no date	WSU-2756	Duplicate of BETA-4414; insufficient sample.
68	Sec. 3, T37S, R21E-1		1,750 ± 60	DIC-1549	Charcoal.
	Cottonwood Wash		3,070 ± 325	DIC-1550	Charcoal.
78	Sec. 12, T38S, R20E-3 Mule Canyon		9,550 ± 80	DIC-2063	Charcoal.

Table 4-6. Radiocarbon Dates Obtained From Quaternary Deposits, Paradox Basin
(Page 4 of 4)

Locality[a]	Site		C-14 Date (yr BP)[b]	Lab No.[c]	Comments[d]
81	Sec. 6, T39S, R21E-1	(#1)	12,770 ± 140	BETA-5582	Limber pine needles and seeds.
	Fishmouth Cave	(#2)	10,360 ± 80	BETA-5761	Pack rat pellets.
	Pack rat middens[g]	(#2)	9,340 ± 290	BETA-5762	Douglas fir needles, twigs, and buds.
		(#3)	10,540 ± 180	BETA-5757	Douglas fir needles, twigs, and buds.
		(#3)	2,790 ± 100	BETA-5758	Utah juniper twigs and seeds.
		(#4)	6,100 ± 100	BETA-5759	Utah juniper twigs and seeds.
		(#5)	9,700 ± 110	BETA-5763	Utah juniper twigs and seeds.
		(#6)	3,550 ± 60	BETA-5764	Utah juniper twigs and seeds.
		(#7)	3,740 ± 70	BETA-5584	Utah juniper twigs and seeds.
		(#9)	2,260 ± 90	BETA-5765	Utah juniper twigs and seeds.

(a) Refer to Table 1-1, Figure 1-1.
(b) BP = Years before 1950 A.D. "Modern" is post-1950.
(c) BETA = Beta Analytic, Inc., Coral Gables, Florida.
DIC = Dicarb Radioisotope Company, Norman, Oklahoma.
WSU = Washington State University, Pullman, Washington.
A = University of Arizona, Tucson, Arizona.
(d) See Table 1-1 for additional information on stratigraphic setting and for comparison of ^{14}C dates with other age estimates.
(e) See Section 2.5, Table 2-9, and Figure 2-6, for stratigraphic data.
(f) Diluted.
(g) Date derived using the barium hydroxide method (Section 4.1.2.2).
(h) See Section 3.2, Table 3-1, and Figures 3-8 and 3-11 for stratigraphic data.
(i) Results of pack rat study are discussed in Betancourt and Biggar (1985) and in Section 2.2 of this report.
(j) ^{13}C = adjusted radiocarbon age. ^{14}C age = 12,060 ± 150 yr BP. $^{13}C/^{12}C$ = 1.78 per mil.

Table 4-7. Results of Carbon-14 Analyses on Disguised Duplicate Samples

Locality[a]	Site		Carbon-14 Date (yr BP)[b]	Lab No.[c]	Comments[d]
2	Sec. 23, T24S, R19E-2		12,880 ± 370 >35,000 (?)	BETA-2629 DIC-2065	Samples represented different sections of mammoth (?) tusk. BETA reported that sample was of very small size; DIC could obtain no carbon from burned sample.
26	Sec. 17, T30S, R20E-1		102% modern no date no date	WSU-2754 DIC-2657 BETA	Charcoal. Both BETA and DIC reported that their samples contained no carbon. WSU had no problem in obtaining sufficient gas from the sample for dating.
27	Sec. 17, T30S, R20E-2		1,710 ± 260 1,790 ± 70	WSU-2809 WSU-2810	Root.
29	Sec. 32, T30S, R20E-2		580 ± 150 1,690 ± 230 2,385 ± 55	DIC-2642 BETA-6220 WSU-2755	Charcoal. Both BETA and DIC reported that their samples were small, resulting in the large standard deviations. Discrepancies in dates probably due to inhomogeneities in original sample.
52	Sec. 27, T34S, R21E-1	(#1)	9,660 ± 140 10,030 ± 100	BETA-5589 DIC-2598	Douglas fir branch, split in half, from fossil pack rat midden.
		(#8)	7,530 ± 200 10,140 ± 190	BETA-5588 A-?120	Douglas fir needles, twigs, and buds. Pack rat pellets.
67	Sec. 31, T37S, R20E-3		9,490 ± 90 7,540 ± 700 no date	BETA-4414 BETA-6221 WSU-2756	Charcoal disseminated in soil. BETA burned entire sample, whereas WSU separated charcoal from sample prior to analysis. This provided insufficient charcoal for dating.

(a) Refer to Table 1-1, Figure 3-1.
(b) BP = Years before 1950 A.D. "Modern" is post-1950.
(c) BETA = Beta Analytic, Inc., Coral Gables, Florida.
DIC = Dicarb Radioisotope Company, Norman, Oklahoma.
WSU = Washington State University, Pullman, Washington.
A = University of Arizona, Tucson, Arizona.
(d) See Table 1-1 for additional information on stratigraphic setting and for comparison of ^{14}C dates with other age estimates.

Of the results received to date from the seven samples submitted in duplicate or triplicate, none demonstrated contemporaneity within one standard deviation (Table 4-7). However, within two standard deviations, duplicate dates were obtained from Locality 67 in Dry Wash; Midden 1 in Allen Canyon Cave, at Locality 52; and Locality 27 in Salt Creek. The lack of reproducibility could have been caused by (1) the small size of the samples after splitting, (2) inhomogeneities of the original sample and accentuation of the inhomogeneities in the split samples, or (3) both. Although the dry weight of a sample before shipment met the minimum weight requirement of the laboratories, the amount sometimes proved inadequate for subsequent analysis after burning. To overcome the problem of inhomogeneity, the samples should have been thoroughly ground and mixed before splitting; the submitted samples had not been homogenized in this manner.

4.1.3 Thermoluminescence Dating

The TL dating technique was originally developed in the 1960s to date pottery, and has become an accepted method of dating archaeological artifacts (Seeley, 1975). It has also been used to date older geologic material, such as limestones of Paleozoic age (Zeller et al., 1957), and Hawaiian basalts of Tertiary age (May, 1977).

In the last 5 years, researchers have developed the means to measure the TL signal of quartz and feldspar grains contained in Quaternary sediments (Wintle and Huntley, 1982). The method measures the amount of TL that has accumulated in the crystal lattice of mineral grains since the mineral was last exposed to intense heat or light. The rate at which TL has accumulated in the mineral, and hence the age of the material, is directly proportional to the amount of radioactive impurities (most commonly isotopes of uranium, thorium, and potassium) present in the mineral and in the nearby environment.

The basis for applying the technique to sedimentary deposits is that exposure to sunlight rapidly removes the signal from the mineral grains. Therefore, if alluvial deposits are well exposed to sunlight prior to or at deposition, TL would be removed from detrital grains, and would start accumulating again only after the material has been buried in depositional processes. In research done to date, TL dates having errors of $\pm$10 to 20 percent have been obtained for homogeneous, fine-grained sediments such as loess and some marine sediments that are less than 50,000 years old and have been dated by other means (Alpha Analytic, Inc., undated pamphlet).

4.1.3.1 Sampling Procedures

The samples collected for TL dating prior to 1982 were to be analyzed using procedures being developed by the USGS for TL dating of carbonate, and hence of calcic soils. However, the USGS program lost impetus, and the samples were instead submitted to Alpha Analytic, Inc., when it opened a commercial TL dating facility in 1982. This laboratory removes the carbonate in the sample and measures TL stored in silt-size quartz and feldspar grains, which is the method reported by Wintle and Huntley (1982). Because the samples collected prior to 1982 had been collected from soil horizons having maximum carbonate development, they were not always collected from stratigraphic units having the most favorable grain size for the procedures used by Alpha Analytic, Inc., or from a stratigraphic position that was most indicative of the age of the Quaternary deposits of interest. For example, the maximum carbonate content in many soil profiles is developed in eolian deposits that overlie alluvial gravels. The eolian deposits were therefore sampled because of their carbonate content, whereas dates for the underlying Pleistocene gravel may have been of particular interest to this study. At some sites, the calcic soil horizon may occur in a horizon where the younger fine-grained material has filtered down into a coarser gravel unit; the derived dates are therefore an "average" of the two different ages for the deposits because they reflect contributions from parent materials of two ages.

Samples collected prior to 1982 were taken from freshly exposed surfaces and stored in aluminum foil. During collection the samples may have been exposed to light for periods of up to 3 or 4 minutes. However, this brief exposure would have had negligible effect on the TL dates (Tamers, 1983). Samples collected in 1982 and later were derived from homogeneous-appearing sand or silt horizons by driving an opaque plastic film container into a freshly expos urface, while shielding the sample from exposure to light.

4.1.3.2 Laboratory Procedures

The TL content of the "glow curve" of a sample is obtained from silt and fine sand grains of quartz or feldspar separated from the field sample. The concentration of alpha, beta, and gamma radiation produced within the mineral is measured, and the radiation sensitivity of the material is determined by applying known doses of radiation to the sample until a glow curve that resembles the natural glow curve is obtained. When the rate at which radiation is produced in the sample is determined, an age is estimated for the sample. A more detailed discussion of these procedures is found in Wintle and Huntley (1982).

4.1.3.3 Means to Assess Accuracy of Results

The accuracy of the TL dates (Table 4-8) can be evaluated by comparing them with other age data received from the same or correlative localities, and by duplicate analysis (Sections 4.1.3.4 and 4.1.3.5). The most comparable data are provided by radiocarbon dates and by ages calculated from soil carbonate accumulation data. The comparison of ^{14}C and TL dates from the same localities is presented in Table 4-9; calcic soil data are compared with TL dates for specific localities in Section 4.2. Qualitative assessments of accuracy were based on the geologic and topographic setting, induration, and sedimentologic character of the sampled deposits.

4.1.3.4 Results

TL dates received for 62 submitted samples are listed in Table 4-8. The dates range from 1,960 to 319,000 years BP. All analyses were done by Alpha Analytic, Inc., Coral Gables, Florida.

Table 4-8. Thermoluminescence Dates Obtained From Quaternary Deposits, Paradox Basin (Page 1 of 4)

Locality[a]	Site	TL date (yr BP)[b]	Lab No. (ALPHA-)[c]	Comments[d]
3	Sec.11, T25S, R16E-1	"unsuitable"	546	Green River terrace, alluvial gravel.
4	Sec.14, T26S, R16E-1	too inhomogeneous	545	Keg Knoll, alluvial sand and pebbles; disguised duplicate samples.
		134,000 ± 19,300	459	
7	Sec.22, T26S, R22E-1	"too young to date"	467	Eolian deposit, collected at depth of 1.2 m (4 ft).
		7,480 ± 610	466	Fine-grained deposit, collected at depth of 2.0 m (6.5 ft).
9	Sec.32, T26S, R23E-1	263,170 ± 45,220	547	Johnson's-Up-On-Top, alluvial gravel.
13	Sec.2, T27S, R22E-1	17,700 ± 1,510	432	Moab permeability pit, alluvial gravel.
		78,200 ± 4,800	433	
		114,320 ± 9,420	532	
14	Sec.5, T27S, R23E-2	167,780 ± 12,430	533	Johnson's-Up-On-Top, alluvial gravel.
15	Sec.16, T27S, R23E-1	238,310 ± 18,520	534	Spanish Valley, alluvial gravel.
16	Sec.17, T27S, R23E-1	42,400 ± 2,770	434	Spanish Valley, alluvial gravel.
17	Sec.18, T27S, R23E-1	108,000 ± 8,400	435	Spanish Valley, alluvial gravel.
18	Sec.18, T27S, R23E-2	11,900 ± 760	436	Spanish Valley, eolian deposit over alluvial gravel.
		9,290 ± 700	535	Spanish Valley, alluvial gravel.
19	Sec.20, T27S, R23E-1	111,000 ± 12,000	439	Spanish Valley, alluvial gravel; disguised duplicate samples.
		127,000 ± 16,400	438	

Table 4-8. Thermoluminescence Dates Obtained From Quaternary Deposits, Paradox Basin (Page 2 of 4)

Locality[a]	Site	TL date (yr BP)[b]	Lab No. (ALPHA-)[c]	Comments[d]
20	Sec.22, T27S, R23E-1	22,500 ± 2,000	440	Spanish Valley, eolian deposit.
		67,600 ± 5,300	437	Spanish Valley, alluvial gravel; duplicate samples collected 0.2 m (0.5 ft) below overlying eolian deposit.
		>315,000	536	
		102,750 ± 13,400	548	Spanish Valley, alluvial gravel.
21	Sec.28, T27S, R23E-1	2,360 ± 220	537	Spanish Valley, eolian deposit.
		319,000 ± 37,000	441	Spanish Valley, alluvial gravel; duplicate samples collected 0.2 m (0.5 ft) below overlying eolian deposit.
		124,210 ± 10,370	538	
		>200,000	539	Spanish Valley, alluvial gravel.
22	Sec.35, T29S, R20E-1	37,400 ± 3,000	442	Gibson Dome, eolian deposit on fan; duplicate samples.
		76,800 ± 10,100	458	
32	Sec.16, T30S, R21E-7	1,960 ± 200	542	Gibson Dome, 8 m (26 ft) terrace, alluvial gravel; duplicate samples collected 0.2 m (0.5 ft) below overlying eolian deposit.
		"too inhomogeneous"	—	
		124,000 ± 13,500	450	Alluvial gravel(?); stratigraphic position of sample is uncertain.
33	Sec.16, T30S, R21E-8	106,000 ± 13,300	452	Gibson Dome, 10 m (32 ft) terrace, alluvial gravel; duplicate samples collected 0.2 m below overlying eolian deposit.
		118,000 ± 8,220	451	
34	Sec.16, T30S, R21E-6	3,600 ± 290	541	Gibson Dome, 10 m (32 ft) terrace, eolian deposit.
		84,100 ± 6,230	449	Alluvial gravel; sample collected 0.2 m (0.5 ft) below overlying eolian deposit.
35	Sec.16, T30S, R21E-5	4,010 ± 310	540	Gibson Dome, 12 m (40 ft) terrace, eolian deposit.
		100,000 ± 8,000	448	Alluvial gravel; sample collected 0.2 m (0.5 ft) below overlying eolian deposit.

Table 4-8. Thermoluminescence Dates Obtained From Quaternary Deposits, Paradox Basin (Page 3 of 4)

Locality[a]	Site	TL date (yr BP)[b]	Lab No. (ALPHA-)[c]	Comments[d]
36	Sec.16, T30S, R21E-4	8,120 ± 740	446	Gibson Dome, 12 m (40 ft) terrace; eolian deposit.
		59,800 ± 4,450	447	Eolian deposit.
37	Sec.16, T30S, R21E-3	215,000 ± 16,600	445	Gibson Dome, 20 m (66 ft) terrace; eolian deposit.
		"too inhomogeneous"	--	
38	Sec.16, T30S, R21E-2	204,200 ± 34,430	551	Gibson Dome, 20 m (66 ft) terrace; eolian deposit.
		163,000 ± 12,400	444	Eolian deposit.
39	Sec.16 T30S, R21E-1	140,000 ± 9,700	443	Gibson Dome, 32 m (105 ft) terrace; alluvial gravel.
		"too inhomogeneous"	--	Duplicate samples collected 0.2 to 0.3 m (0.7 to 1.0 ft) below overlying eolian deposits.
40	Sec.9, T31S, R18E-1	61,540 ± 4,670	526[e]	Grabens; dune deposit in graben valley.
		65,370 ± 4,530	527[e]	
41	Sec.11, T31S, R18E-1	16,300 ± 1,470	468[e]	Grabens, Cow Canyon; valley fill.
44	Sec.14, T31S, R18E-2	3,220 ± 290	528[e]	Grabens, Cow Canyon; valley fill.
45	Sec.28, T31S, R18E-1	11,560 ± 1,080	531[e]	Grabens, Cross Canyon; valley fill.
		16,300 ± 1,260	529[e]	Grabens, Cross Canyon; valley fill.
		46,300 ± 4,630	530[e]	Grabens, Cross Canyon; valley fill.
62	Sec.30, T37S, R19E-6	27,480 ± 2,060	543	WCC Elk Ridge No. 1 (ER-1) drill site, eolian deposit.
		44.930 ± 4,030	544	ER-1 drill site, eolian deposit.

Table 4-8. Thermoluminescence Dates Obtained From Quaternary Deposits, Paradox Basin (Page 4 of 4)

Locality[a]	Site	TL date (yr BP)[b]	Lab No. (ALPHA-)[c]	Comments[d]
67	Sec.31, T37S, R20E-3	3,690 ± 310	464[e]	Dry Wash, fine-grained alluvial/eolian deposit.
		7,050 ± 640	465[e]	Dry Wash, fine-grained alluvial/eolian deposit.
68	Sec.3, T37S, R21E-1	59,100 ± 6,780	463[e]	Cottonwood Wash; fine-grained alluvial deposit.
71	Sec.32, T37S, R22E-1	24,410 ± 2,300	453	White Mesa, soil backhoe pit; eolian deposit.
		32,700 ± 2,850	454	White Mesa, soil backhoe pit; eolian deposit.
72	Sec.33, T37S, R22E-1	46,700 ± 3,950	455	White Mesa, bulldozer trench; eolian/fine-grained alluvial deposit.
		93,800 ± 7,020	456	White Mesa, bulldozer trench; eolian/fine-grained alluvial deposit.
		137,000 ± 10,900	457	White Mesa, bulldozer trench; eolian/fine-grained alluvial deposit.
74	Sec.32, T38S, R11E-1	307,000 ± 39,300	460	Hall's Crossing, eolian deposit.
76	Sec.35, T38S, R11E-1	140,000 ± 11,800	461	Hall's Crossing.

(a) Refer to Figure 1-1, Table 1-1.
(b) BP = Years before 1950 A.D.
(c) Laboratory number assigned by Alpha Analytic, Inc.
(d) See Table 1-1 for stratigraphic relationships.
(e) Sample collected in 1982.

Table 4-9. Comparison of Radiocarbon and Thermoluminescence Dates

Locality (a)	Site	Carbon-14 Date (years BP)(b)	TL Date (years)	Relationship of Sampled Horizons	^{14}C Lab No.(c)	TL Lab No.(d) (ALPHA-)
7	Sec. 22,	1,280 ± 55	"too young to date"	TL above ^{14}C	DIC-1544	467
	T26S, R22E-1	1,280 ± 55	7,480 ± 160	TL below ^{14}C	DIC-1544	466
41	Sec. 11,	2,760 ± 200	16,300 ± 1,470	TL below ^{14}C	WSU-2767	468
	T31S, R18E-1	103% modern	16,300 ± 1,470	TL below ^{14}C	WSU-2796	468
44	Sec. 14,	300 ± 65	3,220 ± 290	TL below ^{14}C	WSU-2766	528
	T31S, R18E-2	3,910 ± 690	3,220 ± 290	TL above ^{14}C	WSU-2764	528
45	Sec. 28,	102% modern	11,560 ± 1,080	Same horizon	WSU-2795	531
	T31S, R18-1	6,420 ± 730	16,300 ± 1,260	Same horizon	WSU-2794	529
		No carbon	46,300 ± 4,630	Same horizon	WSU-2769	530
		1,020 ± 520	46,300 ± 4,630	TL above ^{14}C	WSU-2768	530
67	Sec. 31,	2,380 ± 90	3,690 ± 310	TL below ^{14}C	BETA-4415	464
	T37S, R20E-3	9,490 ± 90	7,050 ± 640	TL below ^{14}C	BETA-4414	465
		7,840 ± 90		(Triplicate ^{14}C dates)	BETA-6221	
		Insufficient sample			WSU-2756	
68	Sec. 3,	1,750 ± 60	59,100 ± 6,780	TL below ^{14}C	DIC-1549	463
			59,100 ± 6,780			
	T37S, R21E-1	3,070 ± 325	(Run twice)	Same horizon	DIC-1550	463

(a) Refer to Table 1-1 and Figure 1-1.
(b) BP = Years before 1950 A.D. "Modern" is post-1950.
(c) Laboratories are listed in Table 4-6.
(d) Laboratory number assigned by Alpha Analytic, Inc.

Both TL and ^{14}C samples were collected at six localities to compare dates derived by the two methods (Table 4-9). The TL dates from Localities 7, 44, 45 (in part), and 67 are stratigraphically consistent when compared with the ^{14}C data. At Locality 67, the older of the duplicated ^{14}C dates is assessed to be more accurate on the basis of amino acid analysis of snail shells found in conjunction with the carbon sample. The TL date, however, is stratigraphically reasonable within the statistical age ranges given for the TL and younger ^{14}C data. However, the TL dates for Localities 7 and 68 do not agree with the interpreted young Holocene age, based on appearance of the deposits. These data suggest that some alluvial sediments did not totally lose their previous TL signal during transport and redeposition, which is a problem with samples deposited under water and rapidly buried. At Locality 45, there is a 45,000-year discrepancy between TL and ^{14}C data. As discussed in Chapter 3 (Section 3.2.1), the ^{14}C date is assessed to be in error because of the geologic setting of the sample, and the TL dates may provide a reasonable age approximation of the deposits.

Comparison of TL dates and age estimates based on calcic soil development indicates that the TL methods can provide realistic approximations of deposits up to 150,000 years old. Dates derived for paleomagnetically reversed deposits (i.e., >730,000 years old) are consistently too young. This may be due to (1) the incorporation of younger eolian sediments into the sampled calcretes during late-Pleistocene time, (2) the recrystallization of calcite during episodes of partial dissolution in mid- or late-Pleistocene time, (3) the saturation of samples with regard to TL after 150,000 to 300,000 years, or (4) the effect of a U-series disequilibrium. Disequilibrium would cause a maximum error of only two times the TL date (Wintle, 1983), and therefore does not provide a full explanation for all of the discrepant dates.

The extent to which the TL dates derived from gravel deposits approximate the estimated age of the deposit is rather surprising considering the apparent nonhomogeneous character of the sample horizon. The TL that accumulates at a given point is affected by the radioactivity of particles in a surrounding radius of 50 cm (20 in) (Wintle and Huntley, 1982). Therefore, the sample should be collected from the center of a horizon that is homogeneous and at least 1 m (3 ft) thick. If the horizon is less than 1 m (3 ft) thick, additional samples should be collected within the effective distance to assess the contribution of radioactivity from the samples' surroundings.

Overall, the results of the TL analysis are sufficiently favorable to continue evaluation and use of the dating method in future studies. Like other chronologic data, TL dates should be carefully evaluated with regard to their geologic reasonability. A factor that may have affected TL dates derived from gravel deposits in the Gibson Dome area is the possible incorporation in the gravel of uranium-rich sedimentary clasts, such as clasts from the Moss Back member of the Chinle Formation. This would result in an erroneously old TL date for the deposit. Generally, reasonable dates were derived from the silt and sand fraction of the gravel samples submitted for dates in the study. Apparently the silt and sand was washed into the interstices between the gravel clasts soon after the gravel was deposited, thereby giving reasonable dates. However, because of the problems of delay in infilling and inhomogeneity of clasts, collection of gravel samples for TL dating is not recommended.

4.1.3.5 Reproducibility of Results

Eight sets of disguised duplicate samples were submitted to assess the reproducibility of the TL dates. Comparative dates were received from five of the sets (Table 4-10); only one of the duplicated sets represented samples from fine-grained deposits. Reproducibility was good for two sets of data; the other three sets, including that for the eolian samples, produced significantly different dates. The cause of these dissimilar dates is unknown. At Locality 22, for example, activities of the two samples were similar, but the equivalent doses derived for the samples differed by a factor of two (Wintle, 1983). At Localities 20 and 21, younger eolian material may have infiltrated nonuniformly into the underlying sampled gravel, causing the disparate dates.

These data stress the importance of adequate calibration and duplication of the TL dates from an area. They also provide some insight into factors that may affect the accuracy of results.

4.1.4 Amino Acid Diagenesis

Amino acid racemization is a widely used tool for age determinations of deposits containing fossil mollusks, foraminifera, and bone (Hare et al., 1980). Investigators have also suggested its use in detecting paleosols and possibly in dating soils (Goh, 1972; Limmer and Wilson, 1980; Miller and Brigham, 1983).

Amino acids are of biological origin, and are present primarily in the L-stereoisomer (L-amino acid) configuration in the live state. After the death of an organism, the L-amino acids gradually invert (or racemize) to the D-stereoisomer configuration at a rate dependent on temperature, until a thermodynamically stable equilibrium mixture of D and L forms is reached. Therefore, materials of increasing age should contain increasing proportions of D-amino acids until a steady state is reached. In the dating technique, the amount of interconversion (epimerization) of L-isoleucine into its diastereomer D-alloisoleucine is determined. Expressed as a ratio of D/L, this fraction provides a measure of the extent of amino acid diagenesis and a relative measure of age.

Because the racemization rate of amino acids is temperature-dependent, a critical portion of any amino-acid dating program is the assessment of the thermal history of the sample. The effective (chemical) temperatures used in the calculation are based on estimated paleotemperatures, depth of burial, and the burial history of the sample. Once a sample is buried at depths greater than approximately 1.5 m (5 ft), the effective temperature approaches a constant value, and rates of epimerization are not significantly affected by diurnal variations or paleoclimatic changes (Brigham, 1980). However, the exposure direction (northern versus southern exposure), thermal conductivity of the enclosing sediment, and microclimatic setting at a specific locality contribute to defining the depth where the effective and the subsurface temperatures are equal (Miller and Brigham, 1983).

Amino acids contained in organic material at a soil surface are adsorbed onto and/or absorbed into the crystalline structure of clay minerals, where they become highly resistant to chemical or biological attack. Ideally,

Table 4-10. Results of Thermoluminescence Analyses on Disguised Duplicate Samples

Locality[a]	Site	TL date (10^3 yr BP)[b]	TL Lab No.[c]	Duplicate TL Date (10^3 yr BP)	Lab No. of Duplicate[c]	Type of Material
4	Sec. 14, T26S, R16E-1	134 ± 19.3	459	"too inhomogeneous"	545	Sand and gravel
19	Sec. 20, T27S, R23E-1	127 ± 16.4	438	111 ± 12.0	439	Gravel
20	Sec. 22, T27S, R23E-1	67.6 ± 5.3	437	>315	536	Gravel
21	Sec. 28, T27S, R23E-1	319 ± 37.0	441	124.21 ± 10.37	538	Gravel
22	Sec. 35, T29S, R20E-1	37.4 ± 3.0	442	76.8 ± 10.1	458	Eolian
32	Sec. 16, T30S, R21E-7	1.96 ± 0.2	542	"too inhomogeneous"	--	Gravel
33	Sec. 16, T30S, R21E-8	118 ± 8.22	451	106 ± 13.3	452	Gravel
39	Sec. 16, T30S, R21E-1	140 ± 9.7	443	"too inhomogeneous"	--	Gravel

(a) Refer to Table 1-1, Figure 1-1.
(b) BP = Before 1950 A.D.
(c) Laboratory number assigned by Alpha Analytic, Inc.

indigenous L-amino acids preserved in this manner slowly racemize during (and following) translocation of the clay particles down the soil profile and into the B horizon (Miller and Brigham, 1983). Because racemization reactions are temperature-dependent, relative age assignments are more accurate if the sites are located in the same microclimatic setting, and the sediments are sampled from a depth of more than 1.5 m (5 ft).

Amino acids in soils are exposed to a broader range of environmental conditions than are amino acids contained within a mollusk shell. Although temperature remains the most critical factor in controlling the rate of epimerization, soil pH, the concentration and species of clay minerals, contamination by soil bacteria, chelation of free amino acids by metal ions, and leaching by ground water may also affect the analytical results.

Research on amino acid racemization has been more extensive on mollusk shells than on soils. Therefore, ages were interpreted with some confidence from amino acid data derived from shell material of selected species (particularly Lymnaea and Succinea). Amino acid ages for soils, however, cannot be extrapolated to such an extent. The soil samples were submitted primarily to assess whether consistent trends in amino acid ratios could be observed in progressively older deposits. In order to test the usefulness of particular soil horizons with respect to another, samples were taken from both B and Cca (or K) soil horizons.

4.1.4.1 Sampling Procedures

Care was taken to avoid direct handling of both the soil and mollusk samples, and to store them in aluminum foil in order to avoid contamination. The mollusk samples were generally washed and initially separated from the deposits in the field. They were subsequently sent to Jim Mead at the University of Arizona for separation and identification of species. Specific identified species were then submitted for amino acid analyses.

The soil samples were collected from freshly exposed material at least 0.3 m (1 ft) below the ground surface. Analyses were performed on the silt and smaller size fractions, following dissolution of $CaCO_3$. Both the sediment residue and the supernatant liquid were analyzed; amino acids were most abundant in the sediment hydrolysate fraction.

4.1.4.2 Means to Assess Accuracy of Results

Accuracy of the derived amino acid dates was assessed by the geologic and topographic settings of the sampled deposit, amount of soil development on the deposit, induration of the deposit, and stratigraphic relationship of the dated material with any available radiocarbon data. At two locations, ^{14}C dates had been derived from the same horizon as the amino acid samples and were used to calibrate paleotemperature assumptions applied to the amino acid analyses.

4.1.4.3 Results

Amino acids in six fossil mollusk shell samples and in 12 soil samples from selected soil horizons were analyzed in 1981 by the Amino Acid Geochronology Laboratory at the Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, Colorado. Mollusk shells were later collected from seven additional sites and submitted for analysis to the Amino Acid Geochronology Laboratory at the University of Massachusetts in Amherst, Massachusetts.

4.1.4.3.1 Analysis of Mollusk Shells. All the shell samples (Table 4-11) were collected from fine-grained alluvial deposits that probably represent fluvially reworked eolian deposits at most localities. All the collection sites, except Localities 2 and 51, are in the Elk Ridge area. Therefore, regional paleoclimatic differences among these sites are probably minor; any variations would be caused more by elevational changes or local microclimates than by regional atmospheric patterns.

The ages estimated for samples sent to the University of Colorado's INSTAAR Laboratory (Table 4-12) are based on a comparison of amino acid ratios derived for the Lymnaea(?) species with ratios derived for the same species in the Lake Bonneville area (McCoy, 1981). The ratios are comparable, and the large-scale paleoclimatic conditions affecting both sets of samples were judged to be comparable, suggesting that the samples collected in the Paradox Basin are similar in age to 11,000-year-old shells from Lake Bonneville. Given this age assumption, paleotemperatures were estimated and used as the basis for age estimates for the other samples sent to INSTAAR.

The age range of 18,000 to 28,000 years BP given for sample AAL-2331 at Locality 78 reflects different temperature assumptions. The younger age (18,000 years BP) is based on the assumption that the paleotemperature has been the same for the last 18,000 years BP. However, temperatures were probably at least 5°C (9°F) cooler during the full glacial period. When this probability is factored into the calculations, an age of 28,000 years BP is derived for the sample, and is believed to be more reasonable.

The high D/L ratio for Lymnaea(?) in sample AAL-2330 (Locality 78) seems anomalous; the sample was collected 15 cm (6 in) above a burn layer that has a ^{14}C date of 9,550$\pm$80 years BP (Table 1-1), and may therefore represent a shell that was previously heated and has been reworked from the charcoal layer. The amino acid ratios for Gyraulus also do not appear to have a consistent trend; sufficient research has not been conducted on this species to explain the obtained ratios with more confidence (Miller, 1981).

Samples submitted to the Amino Acid Geochronology Laboratory, University of Massachusetts, included a variety of species (Table 4-11). The age estimates given for these samples are based on the alloisoleucine/isoleucine (aIle/Ile) ratios in Succinea, and the inferred temperature history of the sample (Table 4-12). The amino acid data for the other genera were used to check for sample contamination and to characterize different genera of mollusks. No significant quantities of contaminating amino acids were found in the samples. The radiocarbon dates at Localities 63 and 67 were used to calibrate the paleotemperature data. The uncertainties shown in the estimated

Table 4-11. Summary of Amino Acid Ratios Derived From Mollusk Shells

Locality	Site	Lab No.(b)	Lymnaea(?)	Gyraulus	Succinea(c)	Pupilla(c)	Vallonia(c)	Fossaria	Discus	Vertigo	Physa(c)	Pisidium
			aIle/Ile(a)									
2	T24S,R19E, Sec.23-2	AAL-2332	0.12, 0.14			0.14						0.15
51	T34S,R19E, Sec.20-1	20-1-1									[0.73 ± 0.08] [0.92 ± 0.02]	0.77
53	T37S,R20E, Sec.11-3	11-3-1			0.115 ± 0.010			0.099				
64	T37S,R20E, Sec.24-1	24-1-1			0.060 ± 0.001	0.066 ± 0.007	0.071 ± 0.016	0.085 ± 0.001		0.071 ± 0.003		
65	T37S,R20E, Sec.30-1	30-1-21			0.129 ± 0.010	0.126 ± 0.003	0.141 ± 0.003	0.113	0.157 ± 0.011			
66	T37S,R20E, Sec.31-1	31-1-14			0.126 ± 0.004	0.100 ± 0.018	0.057 ± 0.002	0.122 ± 0.011				
67	T37S,R20E, Sec.31-3	31-3-2			[0.079 ± 0.003] [0.093 ± 0.002]	0.069 ± 0.003	[0.064 ± 0.003] [0.053 ± 0.002]	0.110 ± 0.035	0.113 ± 0.016			
78	T38S,R20E, Sec.12-3	AAL-2330	0.225	0.126								
		AAL-2331				0.20						
		AAL-2329	0.13									
		AAL-2334		0.21, 0.20								
79	T38S,R20E, Sec.25-1	AAL-2335	0.13									
		25-1-3			0.140 ± 0.12	[0.093 ± .005] [0.098 ± .004]	0.099 ± 0.004					

(a) Mean peak height ratios of alloisoleucine (aIle) to isoleucine (Ile) in the total acid hydrolysate of the sample with the range about the mean determined by duplicate preparation and analysis of each sample.
(b) AAL indicates sample was analyzed by the Amino Acid Laboratory, INSTAAR, University of Colorado. The other samples were analyzed by the Amino Acid Geochronology Laboratory, University of Massachusetts.
(c) Brackets indicate analyses of disguised duplicate samples.

Table A-12. Interpretation of Amino Acid Data for Mollusk Shells

Locality	Site	Lab No.[a]	E[b]	Depth[c]	MAT[d]	R_T[e]	T_{eff}[f]	A. Age estimated from AA data (yr)	B. Age derived by other means (yr)	Comments
2	T24S,R19E,Sec.23-2	AAL-2332	1,450	ca 7.5	(12.5)[g]	(25.8)[g]		ca 11,000 to 15,000[h]	^{14}C: 12,880 ± 370, >35,000 U-Th: 43,000 ± 1,000 to 48,000 ± 4,000	Shells were collected 3.5 m (12 ft) above mammoth tusk. Other dates given were derived from tusk.
51	T34S,R14E,Sec.20-1	20-1-1	1,140	14.6	14.5	27.1	ca 10(?)	500,000 - 300,000[h] - 200,000	ca 300,000	"B" age based on height of sample above present stream level.
65	T37S,R20E,Sec.11-3	11-3-1	1,585	6.9	11.6	25.3	11.0	12,500 ± 160[i]	^{14}C: 12,500 ± 160	^{14}C date used for calibration of amino acid data for paleotemperature interpretation.
64	T37S,R20E,Sec.24-1	24-1-1	1,525	6.4	12.0	25.6	12.0	5,000 ± 2,000[j]	^{14}C: >410 ± 60	^{14}C data is from cut-and-fill terrace that is inset into terrace containing shells.
55	T37S,R20E,Sec.30-1	30-1-21	1,830	6.1	10.0	24.4	8.1	24,000 ± 7,000[j]	≥125,000 ($CaCO_3$ accumulation)	"B" age estimate based on visual assessment of $CaCO_3$ accumulated in soil profile and comparisons with similar, nearby profiles where pedogenic $CaCO_3$ was measured.
66	T37S,R20E,Sec.31-1	31-1-14	1,830	2.4	10.0	24.4	9.3	19,000 ± 6,000[j]	115,000 to 195,000 ($CaCO_3$ accumulation)	Proximity of stream may have caused excessive accumulation of pedogenic $CaCO_3$ at base of soil profile. "B" age, based on lab analyses, is likely to be too old.
67	T37S,R20E,Sec.31-3	31-3-2	1,830	1.2	10.0	24.4	12.4	9,490 ± 90[i]	^{14}C: 9,490 ± 90 7,840 ± 700 (duplicate) TL: 7,050 ± 640	^{14}C date of 9,490 ± 90 used for calibration of paleotemperature. TL sample collected 0.6 m (2 ft) below shells.
78	T38S,R20E,Sec.12-3	AAL-2330	1,490	ca 6	(12.2)[g]	(25.6)[g]		ca 11,000[h]	^{14}C: <9,550 ± 80	Shells collected from upper part of channel, 0.15 m (0.5 ft) above ^{14}C sample.
		AAL-2331	1,490	ca 11				18,000 to 28,000[h]	^{14}C: >9,550 ± 80	Older deposit, truncated by younger channel deposit containing other collected samples.
		AAL-2329	1,490	ca 10				ca 11,000[h]	^{14}C: >9,550 ± 80	Collected from base of channel.
		AAL-2334	1,490	ca 10				ca 11,000[h]	^{14}C: >9,550 ± 80	Same collection site as AAL-2329.
79	T38S,R20E,Sec.25-1	25-1-3	1,525	≥1.5	12.0	25.5 ≥8.0	≤14.2	≥9,000[j] ≤30,000[j]		Deposits may project to terrace surface that is approximately 12 to 24 m (40 ft to 80 ft) above present stream level. No other datable material found in deposits.
		AAL-2335		1.5				ca 11,000[h]		

(a) AAL: Amino acid laboratory, INSTAAR, University of Colorado. All other samples analyzed by Amino Acid Laboratory, University of Massachusetts.
(b) Elevation of site in meters.
(c) Depth (m) below present ground surface or the surface of the oldest buried soil.
(d) Mean annual air temperature (MAT) (^oC) based on site elevation and the relationship between elevation (E) and MAT as determined by linear regression using data from Monticello, Blanding, Bluff, Cedar Point, and Mexican Hat for the period 1951-1960; linear regression equation is MAT = -0.0065E +21.9; r^2 = 0.97.
(e) Range in temperature (^oC) at each site based on the relationship between elevation and the maximum difference between mean monthly temperatures as determined by linear regression using data for 1951-1960 from the sites listed in note 3; linear regression equation is R_T = -0.004E +31.6; r^2 = 0.93.
(f) Effective temperature (^oC) for each sample calculated from MAT, R_T, depth below ground surface (or any known paleo-ground surface), and an activation energy for isoleucine epimerization of 28.6 kcal. Calculation assumes that annual temperature variation of depth of sample follows a sine curve. The mean annual temperature since 11,000 years BP is assumed to be equal to the MAT for 1951-1960 and the mean annual temperature prior to 11,000 years BP is assumed to be 10^oC less than present.
(g) Numbers in parenthesis were calculated from formulas given in (d) and (e), and are given for information purposes only.
(h) Amino acid (AA) age estimate based on alle/Ile ratio of _Physa_ sample in comparison with that of other _Physa_ and _Lymnaea_ shells found in association with known tephra beds in northern Utah, taking the difference in MAT into account.
(i) Amino acid (AA) age estimate based on radiocarbon date, this report (Table 4-6).
(j) Amino acid (AA) age estimate based on alle/Ile ratio of _Succinea_ sample assuming that isoleucine epimerization kinetics for _Succinea_ shells are the same as for _Lymnaea_ shells; the larger uncertainties in age are largely a function of the uncertainty in temperature history, i.e., T_{eff}.

ages reflect the uncertainty in the actual thermal history of each sample, and in the depth at which it has been buried since deposition (only the present depth below the ground surface is known). The thermal history has been inferred from other paleoclimatic data from Utah and neighboring States.

4.1.4.3.2 Analysis of Soil Samples. In order to assess the usefulness of amino acid analysis for relative soil dating, samples were collected from carbonate- or clay-rich horizons of eight soil profiles in Spanish Valley. The results of the analyses (Table 4-13) indicate that the organic material in near-surface calcic horizons is young. The low ratios may reflect contamination by newly infiltrated organic matter and/or the continuing accumulation of soil carbonate that carries young amino acids with it into the calcic horizons. Ratios in a B horizon formed in the lower member of the Beaver Basin Formation (Locality 18), a buried B horizon of the Placer Creek Formation (Locality 13), and the buried clay-rich stratum in the middle member of the Harpole Mesa Formation (Locality 21) are significantly higher, suggesting that clay may be more effective than carbonate in isolating organic matter. The high D/L ratio in the Harpole Mesa deposit at Locality 21 also supports the interpretation that the horizon is a paleosol, rather than a clay-rich deposit (Section 4.2.1.1.1).

4.1.4.4 Reproducibility of Results

To assess reproducibility of the amino acid analyses of mollusk shells, disguised duplicates of four different snail species were included with the samples sent to the University of Massachusetts. These sample sets are shown in brackets in Table 4-11. Variances in the data range from 5 percent (Locality 79) to 25 percent (Locality 2). The laboratory also ran duplicates of all the samples and incorporated the results in the data analysis. Of the laboratory measurements, 81 percent were duplicated within 10 percent, and 60 percent were duplicated within 5 percent. The data were assessed to be sufficiently accurate to be used in age determinations.

Only a few soil samples were analyzed for amino acid content. Therefore, reproducibility of the soil amino acid data was not evaluated.

4.1.5 Paleomagnetic Analysis

The paleomagnetism of Quaternary deposits can be used to correlate and establish a minimum date for units that may be of early Pleistocene age. The polarity of a sediment's remanent magnetization reflects the polarity of the Earth's magnetic field when the sediment was deposited. The last major period of reversed polarity occurred from 2.3 to 0.73 million years ago. An earlier reversal that may be recorded in the older deposits of the Paradox Basin is the Gilbert epoch, which lasted from 5.1 to 3.3 million years BP (Mankinen and Dalrymple, 1979). Reversed paleomagnetic polarity in Quaternary deposits therefore indicates that they are at least 730,000 years old and may be several million years old. Paleomagnetic analysis has been used for the last 20 years to define the break between the normal and reversed-polarity epochs at 730,000 years. It is a technique that is generally accepted by the scientific community.

Table 4-13. Amino Acid Ratios of Spanish Valley Soils

Locality	Site	Formation[a]	Horizon	Depth (cm)	alle/Ile
13	T27S,R22E, Sec.2-1	Beaver Basin Upper Member, Placer Creek	4Ccab2 4K2mb3 5B2tcab4	140 180 375	0.075 0.017[b] 0.275
14	T27S,R23E, Sec.5-2	Lower Member, Harpole Mesa	2K22mb	110	0.03[b]
15	T27S,R23E, Sec.16-1	Upper Member, Placer Creek	2C1ca	50	0.057
16	T27S,R23E, Sec.17-1	Upper Member, Beaver Basin	2C1ca	40	0.028
17	T27S,R23E, Sec.18-1	Lower Member, Placer Creek	2K2mb	30	0.031
18	T27S,R23E, Sec.18-2	Lower Member, Beaver Basin	2B3ca	60	0.177
19	T27S,R23E, Sec.20-1	Lower Member, Placer Creek	2K2b	50	0.051
20	T27S,R23E, Sec.22-1	Middle Member, Harpole Mesa	2K2mb	30	0.035
21	T27S,R23E, Sec.28-1	Middle Member, Harpole Mesa	2K2b 3B1csb2	50 250	0.057 0.45

(a) = See Table 4-16.
(b) = Poorly resolved, despite repeated analysis.

On a shorter time scale, the remanent magnetism acquired by late Pleistocene and Holocene deposits records short-term regional variations in the declination, inclination, and intensity of the Earth's magnetic field (Irving, 1964). These fluctuations are referred to as secular variations. They reflect the fluctuations in the nondipole component of the Earth's magnetic field and have been used to correlate stratigraphic sections with dated sequences where the magnetic signatures are known. The pattern varies from one region to another, so correlations over large distances are not reliable. If these secular variations can be identified for a particular region and dated at controlled sections, the magnetic signatures of undated localities can be correlated with the reference sections. The interpretation of derived secular variation data, however, requires the knowledge of the approximate time interval represented by the deposit, and a well-dated correlation section.

4.1.5.1 Sampling and Laboratory Procedures

Samples of unconsolidated, fine-grained sediments were collected and sampled for paleomagnetic analyses. The undisturbed samples were carved from outcrops and simultaneously fitted into plastic containers having a volume of 5 cm^3 (0.31 in^3). The orientation of the sample relative to magnetic north and to the horizontal was measured using a pocket transit (Brunton compass). Duplicate or multiple samples were collected at all sites and measured to test for consistency.

The magnetization of a deposit reflects several variables. The primary magnetization recorded by sediments reflects the influence of the Earth's magnetic field, and is acquired as the grains are deposited. Postdepositional chemical alterations, bioturbation, shrinking and swelling, and other processes may add later magnetic signatures that are difficult to identify separately. To understand and separate these complications, it is necessary to slowly demagnetize the samples in a laboratory.

Each Paradox Basin sample was demagnetized in an alternating field magnetometer at the WCC paleomagnetic laboratory in Pleasant Hill, California. The demagnetization process measures the distribution of a sample's magnetization relative to its coercivity (resistance to demagnetization). As many as 10 measurements per sample were made in the demagnetization process. Postdepositional processes appeared to have had some effect on the magnetization of some Paradox Basin samples. Samples that displayed significant changes in magnetic direction during demagnetization are discussed in the following sections.

4.1.5.2 Means to Assess Accuracy of Results

The accuracy of laboratory measurements made to establish the paleomagnetic polarity of a deposit was assessed by examining (1) the reproducibility of results for duplicate or multiple samples collected at each sampled site, and (2) the geologic reasonableness of the data with regard to the topographic setting and pedogenic development in the deposit.

Measurements of secular variation within Holocene deposits were examined with respect to coherency of overall trends in the data. As more secular variation data become available for Holocene deposits in the Southwest, the trends derived from samples collected during the Paradox Basin studies should be compared with other bodies of data to assess their accuracy.

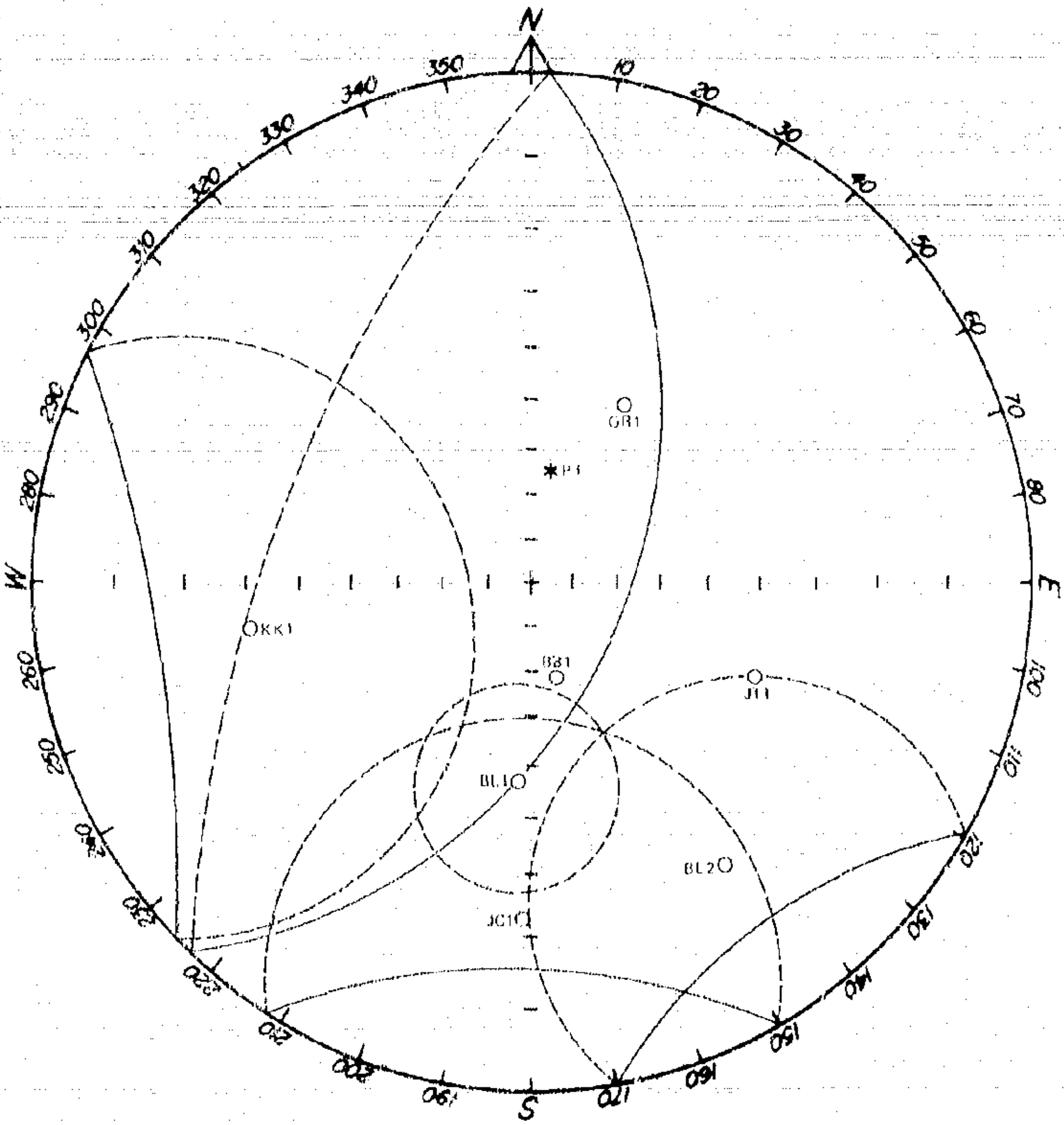
4.1.5.3 Results

Paleomagnetic analyses were conducted on samples collected from 21 sites in the Paradox Basin (Table 1-1). The technique proved most useful in identifying sediments deposited during a reversed-polarity epoch (early to middle Quaternary time). These deposits, which were sampled at seven sites, can be clearly differentiated from the younger sediments collected at the other locations on the basis of magnetic signatures (Figures 4-3 and 4-4). Correlation of younger deposits using secular variations would probably be quite successful with additional sampling and analysis. Because Holocene deposits can commonly be dated by the radiocarbon technique, application of paleomagnetic studies to deposits of this age has not been pursued further.

4.1.5.3.1 <u>Paleomagnetism of Early Quaternary Deposits</u>. Well-developed pedogenic calcretes observed at several localities in the Paradox Basin indicate that the deposits at those sites are at least 500,000 years old (WCC, 1982a, Vol. I). Deposits between 0.73 and 2.5 million years old should have reversed paleomagnetic signatures (Mankinen and Dalrymple, 1979); therefore, samples were collected from seven sites (Table 4-14) to determine whether the deposits are more than 730,000 years old. Assignment of minimum ages to these deposits enables computation of maximum long-term erosion rates and maximum rates of calcic soil development.

Table 4-14. Interpretation of Paleomagnetic Measurements of Early Pleistocene Deposits

Lab No.	Site	Locality	Samples	Polarity
BB1	Bullfrog Basin	73	3	Reversed(?)
BL1	Blanding Gravels 1	55	4	Reversed
BL2	Blanding Gravels 2	54	4	Reversed
GR1	Green River	12	3	Questionable
JC-1	Johnson Creek	53	3	Reversed
JT1-1	Johnson's-Up-On-Top	9	2	Questionable
JT1-3,4	Johnson's-Up-On-Top	9	2	Questionable
JT1-5,6	Johnson's-Up-On-Top	9	2	Reversed
KK1-1	Keg Knoll	5	4	Questionable
KK1-4	Keg Knoll	5	2	Reversed(?)



LEGEND:

The symbol O is the mean magnetization direction and the circle surrounding it is the Alpha–95 circle of confidence. Plots are Wulff (equal angle) stereonets. Solid circles and lines indicate projection of pole onto the lower hemisphere (normal magnetic polarity); open circles and dashed lines indicate pole projection onto upper hemisphere (reversed magnetic polarity). Symbols without circles indicate that data were not of sufficient quality to draw circles of confidence.

*P.F. = Present Field Direction

SAMPLE DESIGNATION (LOCALITY)

BB1 = Bullfrog Basin (73)
BL1 = Blanding gravels (55)
BL2 = Blanding gravels (54)
GR1 = Green River (12)
JC1 = Johnson Creek (53)
JT1 = Johnsons-Up-On-Top (9)
KK1 = Keg Knoll (5)

(73) = Locality number (Table 1–1)

LOCALITIES ARE SHOWN ON FIGURE 1–1
DATA INTERPRETATIONS ARE PRESENTED ON TABLE 4–14

LOG 1669a
REV. 0–10/19/83

STEREONET PLOTS OF MEAN MAGNETIZATION DIRECTION AFTER DEMAGNETIZATION FOR EARLY PLEISTOCENCE DEPOSITS

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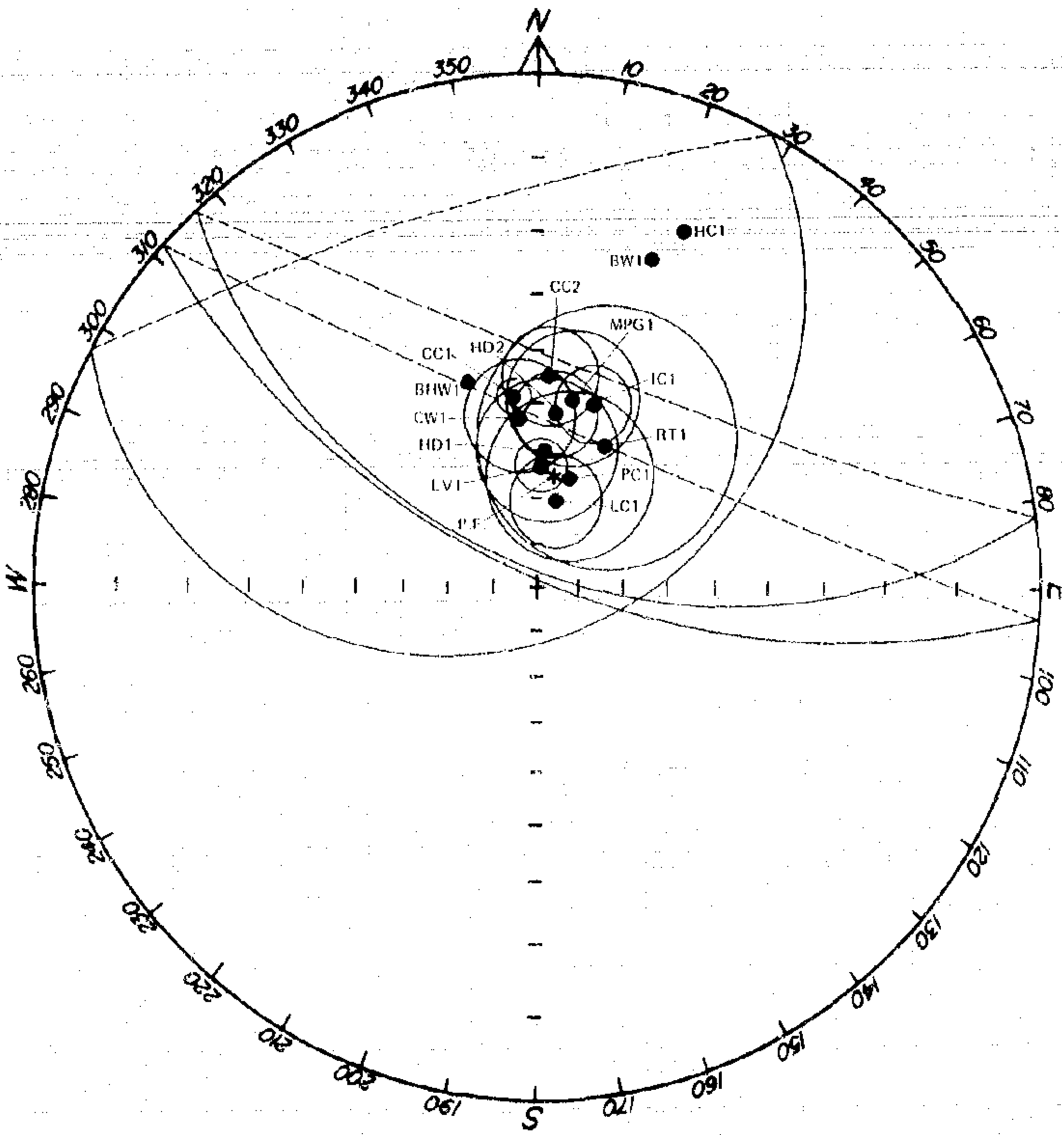
Figure 4–3



LEGEND:

The symbol ● is the mean magnetization direction and the circle surrounding it is the Alpha—95 circle of confidence. Plots are Wulff (equal angle) stereonets. Solid circles and lines indicate projection of pole onto the lower hemisphere (normal magnetic polarity); Open circles and dashed lines indicate pole projection onto upper hemisphere (reversed magnetic polarity).

SAMPLE DESIGNATION (LOCALITY)

BHW1 = Wash north of BW1 (1)
BW1 = Bartlett Wash (2)
CC1 = Lower Cottonwood Creek (47)
CC2 = Upper Cottonwood Creek (47)
CW1 = Cottonwood Wash (68)
HC1 = Halls Crossing (75)
HD1 = Harts Draw 1 (48)
HD2 = Harts Draw 2 (49)
IC1 = Indian Creek (31)
LC1 = Lackey Creek (23, 24)
LV1 = Lisbon Valley (26)
MGP1 = Moab Gravel Pit (6)
PC1 = Picket Fork (77)
RT1 = Rattle Property (7)

(47) = Locality number (Table 1—1)

LOCALITIES ARE SHOWN ON FIGURE 1-1

* P.F. = Present Field Direction

STEREONET PLOTS OF MEAN MAGNETIZATION DIRECTIONS AFTER DEMAGNETIZATION OF HOLOCENCE DEPOSITS
Quaternary Topical Report

LOG 1670a
REV.0—10/19/83

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Figure 4—4

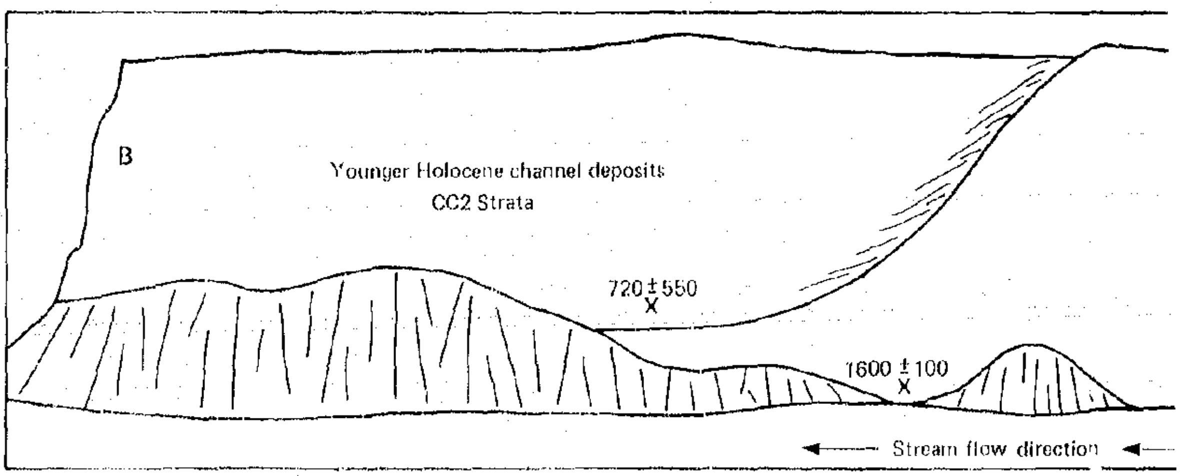
Of the seven sites sampled, six yielded paleomagnetic data that were interpreted as representing reversed polarity (Figure 4-4), confirming a minimum age of 0.73 million years for the deposits. However, some of the samples from these sites displayed a complex magnetization that could not be interpreted as either normal or reversed polarity (Table 4-14). These questionable samples appear to have several magnetic components, some of which were acquired during postdepositional chemical weathering. In several cases, the easily removed (low coercivity) magnetic component is normal, while the more stable (intermediate and high coercivity) components are reversed. These samples probably acquired their initial magnetization during a period of reversed polarity, and secondary magnetic signatures were added since polarity became normal. However, the polarity of some samples is questionable, and at Keg Knoll and Johnson's-Up-On-Top, several samples had to be analyzed before a sample was obtained that exhibited a definitive polarity. Although the polarity could not be clearly defined for the Green River location, the paleomagnetic character of this deposit was assumed to be the same as deposits at Keg Knoll, which have a similar pedogenic appearance and topographic position, and where the polarity of the sediments is reversed.

4.1.5.3.2 Paleomagnetism of Holocene Deposits. A Holocene section sampled at 1.5-m (5-ft) intervals on Cottonwood Creek (Locality 47, Figure 4-5) in the Gibson Dome area yielded a consistent secular variation curve for the time interval between 1,600 and 1,270 years BP, and a less definite trend in fill thought to be younger than 720 years BP (Figures 4-6 and 4-7). At this location the CC2 strata represent fill in a channel cut into the CC1 strata (Figure 4-5). The CC1 section illustrates the gradual eastward shift in declination between 1,600 and 1,270 years BP. The data show a declination increase from approximately 300 degrees (60 degrees west) for sediments approximately 1,600 years old to approximately 0 degrees for sediments somewhat younger than 1,270 years BP at the top of the exposure.

The trend seen in the CC1 data appears to continue in the data for the younger CC2 fill; however, the number of data points in the CC2 strata is not large enough to confirm this conclusion. An indicator ^{14}C date of 720 ± 550 years BP was obtained from the bottom of the fill. It represents the only age control on the section. The declination data vary between approximately 5 degrees west at the bottom of the fill, to 15 to 20 degrees east at the top of the fill. These data include an apparent trend to approximately 25 degrees east in the lower half of the section.

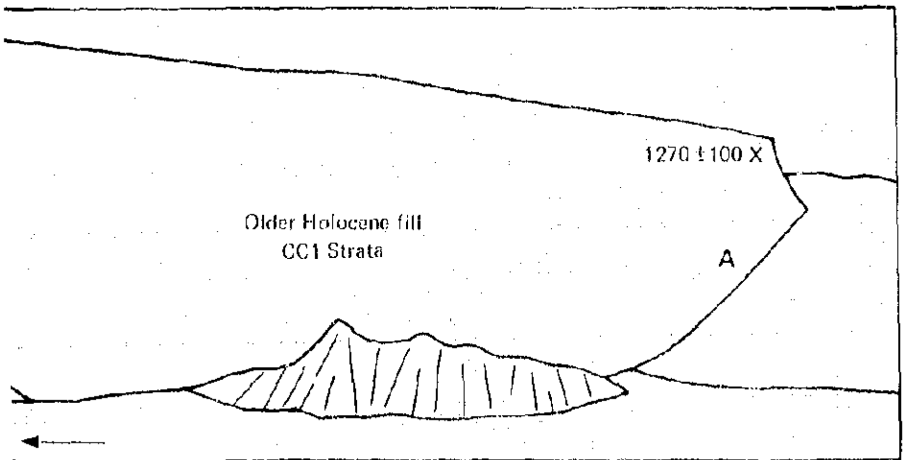
Because the inclination recorded by sediments can be significantly affected by grain shape and rates of deposition (Irving, 1964), declination variation is more reliable than inclination changes for the sites. This is reflected in the less consistent trends observed in the inclination data (Figures 4-6 and 4-7).

In order to construct a complete secular variation curve for the Paradox Basin for the past 5,000 or more years, further sampling and ^{14}C dating would be required. It would be necessary to eliminate the apparent gaps in the record obtained to date, and to obtain a more detailed record for the period before 1,600 years BP. In order to ensure the reliability of the curve, it would also be desirable to obtain more data from overlapping sedimentary sections, and duplicate analyses for each time period.



Location of ^{14}C and paleomagnetic sampling sites in alluvial deposits a
Bedding and surface of older fill at right of photograph has been cut and
left half of photograph. ^{14}C sample sites (X) and obtained dates are sh
collected from the older fill along the slough bank at A. The younger un
exposure approximately 25 m (80 feet) downstream from B. The expos
at A.

Note: ^{14}C dates are stated in years BP.

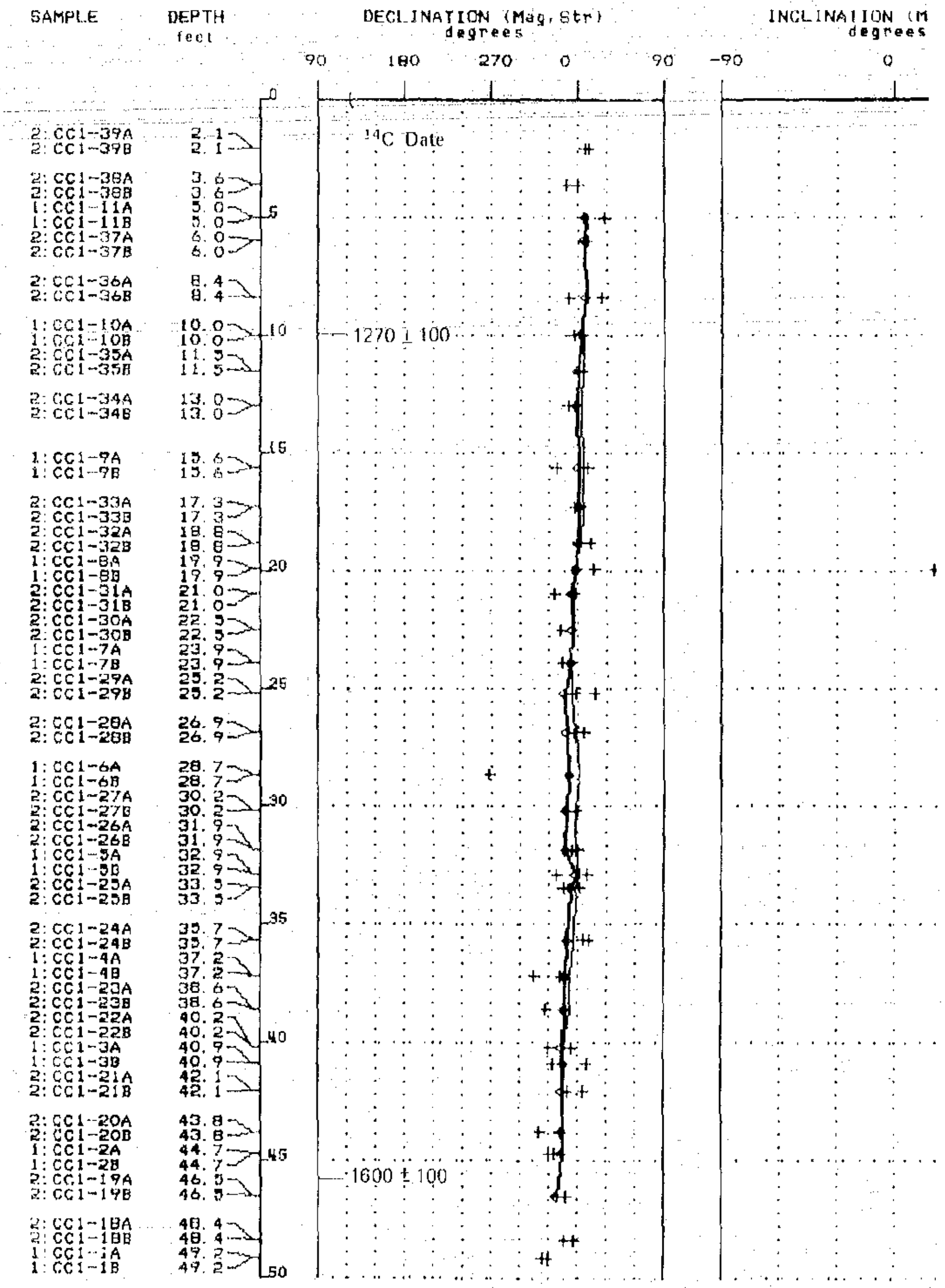


ıosits at Locality 47 on Cottonwood Creek.
ıut and filled by similar-appearing deposits on
are shown. Paleomagnetic samples were
ıger unit was sampled in an accessible arroyo
exposure of older fill is 17 m (57 feet) thick

HOLOCENE DEPOSITS, COTTONWOOD CREEK
GIBSON DOME AREA

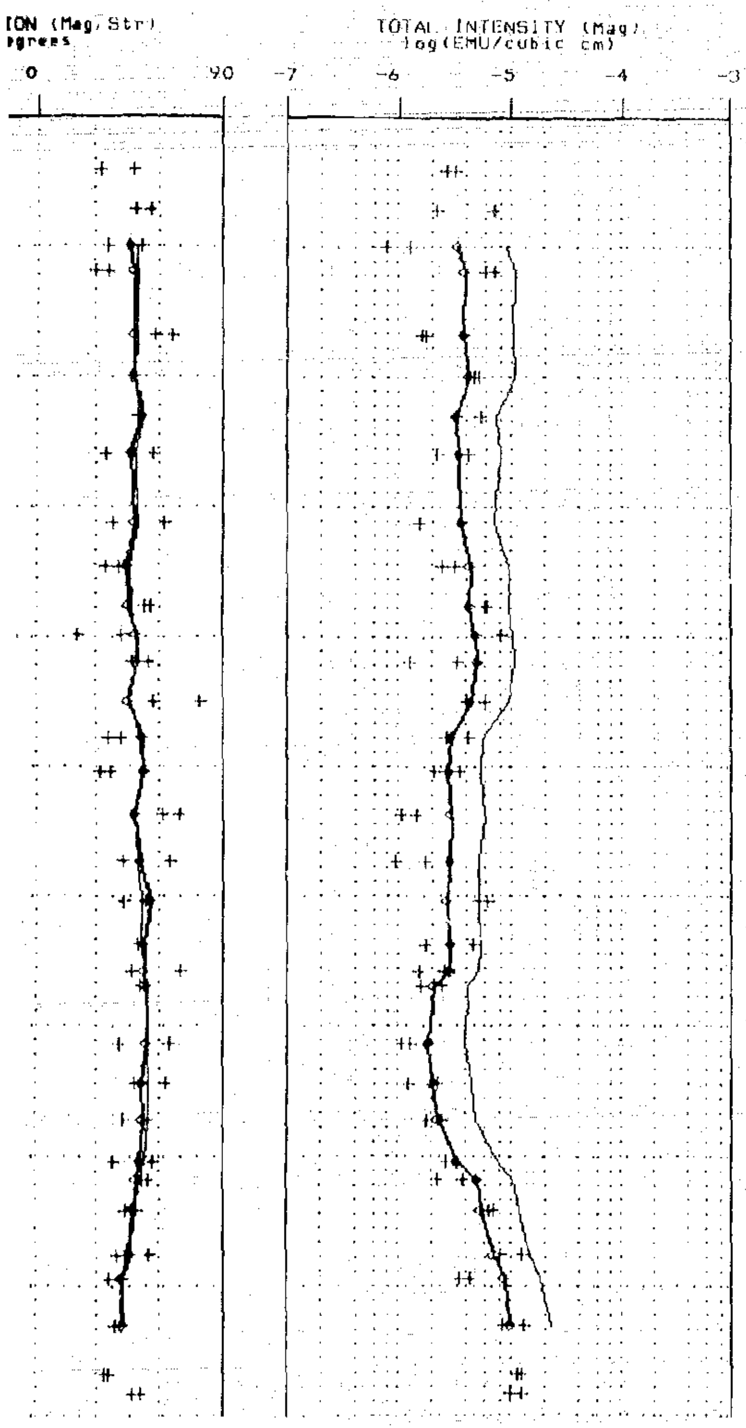
Quaternary Topical Report

Project No. 17000	Figure 4-5



Key + = Selected demag; * = NRM; A–R = Additional demag levels
Φ = Average selected demag, connected by ———
Average NRM connected by ———
Running average of 5 samples

See Table 4–6 for ^{14}C Laboratory Numbers



AVERAGED PALEOMAGNETIC DATA FOR OLDER HOLOCENE FILL, LOCALITY 47, COTTONWOOD CREEK

Quaternary Topical Report

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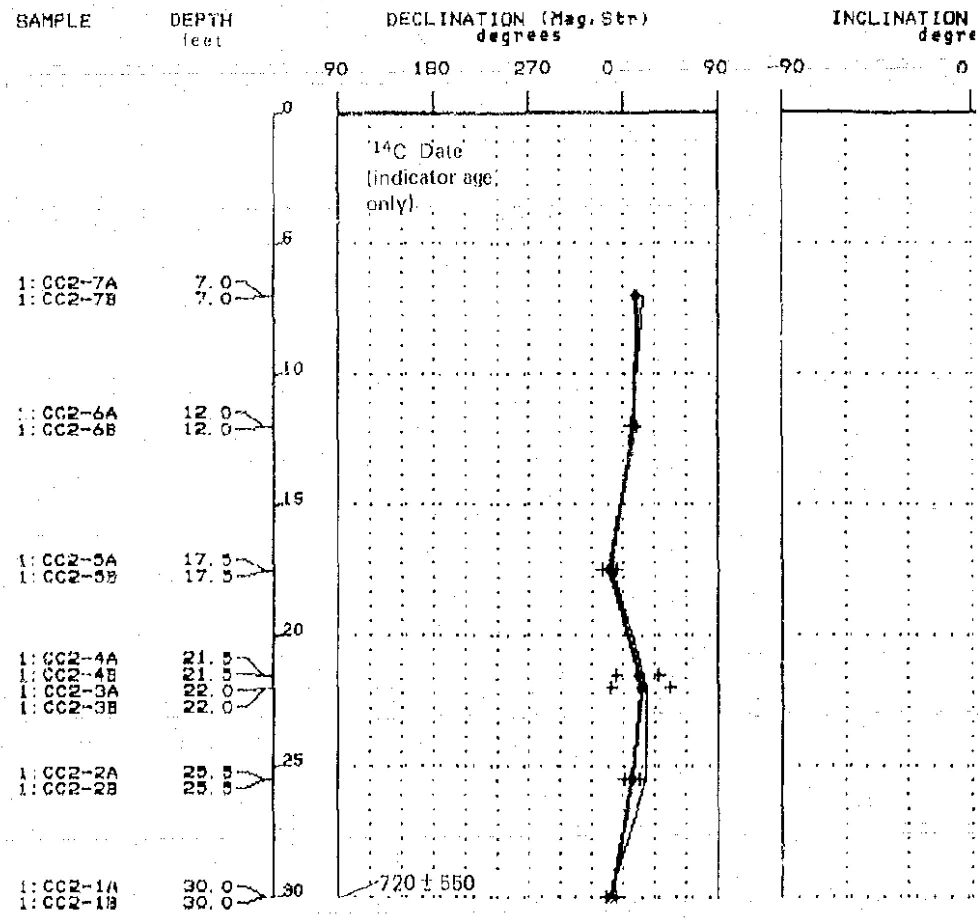
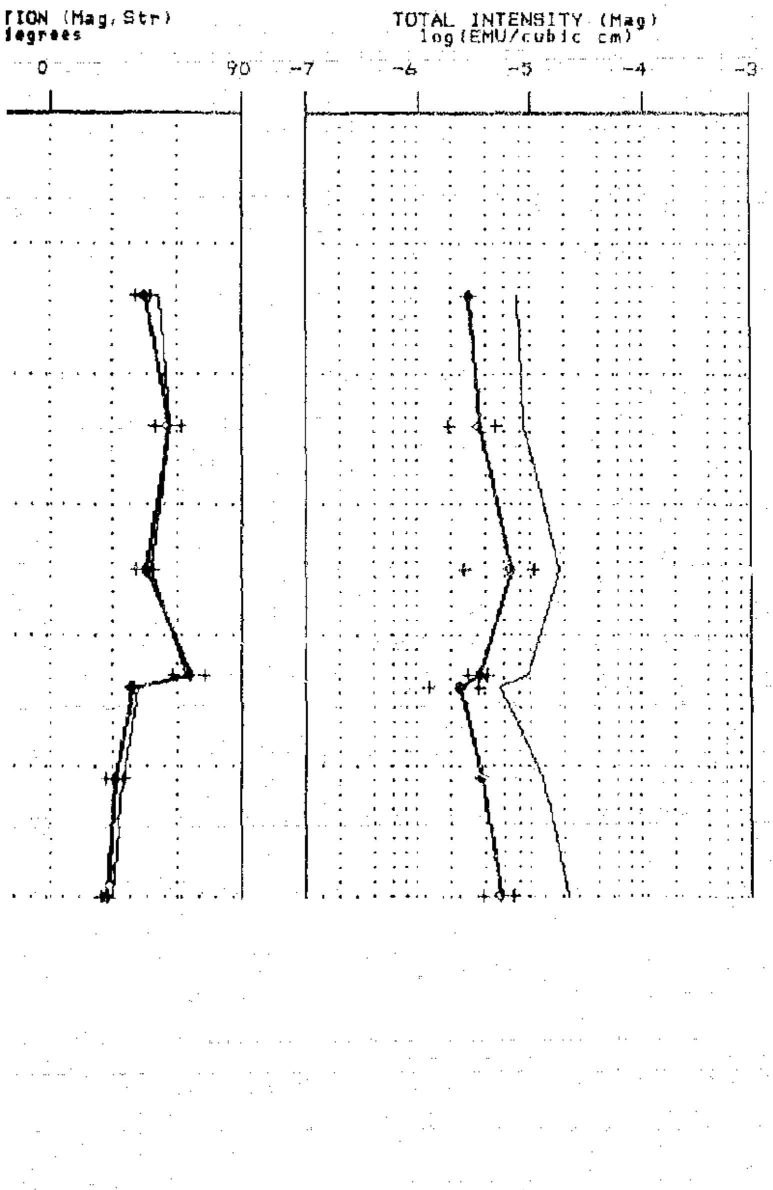
Figure 4-6



Key + = Selected demag, * = NRM, A-R = Additional demag levels
◊ = Average selected demag, connected by ———
Average NRM connected by ———

See Table 4-6 for ^{14}C Laboratory Numbers



PALEOMAGNETIC DATA
FOR YOUNGER HOLOCENE FILL,
LOCALITY 47, COTTONWOOD CREEK

Quaternary Topical Report

Project No. 17000 Woodward-Clyde Consultants	Figure 4-7

4.1.6 Uranium-Series Dating

Ku et al. (1979) report that a U-series dating technique has been used successfully to date calcic soils developed on gravel deposits in an arid to semiarid climate. The data obtained were consistent and agreed with geomorphic and stratigraphic relative age relationships. The technique utilizes radioactive disequilibrium relationships among the ^{230}Th, ^{234}U, and ^{238}U isotopes in carbonate rinds cemented to gravel clasts, and is potentially applicable to the last 350,000 years (Ku et al., 1979).

This dating technique is attractive to the Paradox Basin dating program because of its relatively long time span of applicability, the relative abundance of calcic soils that have developed on fluvial gravel deposits in the area, and the lack of available materials that can be dated using other methods. The primary drawback to the method is that it has not been used extensively on soils; therefore, the reproducibility of derived data should be evaluated.

As a preliminary assessment of the usefulness of this technique for the project, three samples were collected in 1979 from gravel terraces and sent to Ku at the University of Southern California, Los Angeles, California, for an initial evaluation of the method. Field estimates of the ages of the samples were based on the stage of calcic soil development in the deposit, the height of the terrace above present stream levels, and ages assigned in previously published studies. A fourth sample, a piece of a mammoth(?) tusk that had been collected near Moab, was also analyzed.

4.1.6.1 Sampling and Laboratory Procedures

Cobbles with carbonate rinds are split open in the field to evaluate the suitability of the rind for dating. The innermost layer of the rind, which is used in the dating analysis, should be fresh-appearing, dense, massive in texture, and well cemented to the clast. Rinds that are thicker than 3 or 4 mm (0.12 in) are preferable; those that are less than 0.1 mm (0.04 in) in thickness should not be used (Ku et al., 1979). No special handling or sample preparation is needed prior to submittal for analysis.

Laboratory methods that were used to assess the age of the carbonate rinds were slightly modified from those discussed in Ku et al. (1979); the radiochemical purification procedures applied to the tusk sample are presented in Ku (1968). Dating of both the carbonate rinds and the tusk material is based on the decay of ^{238}U to ^{230}Th, and utilizes the relative abundance of these radioisotopes in a sample. Another isotopic ratio that uses ^{235}U and its daughter product, ^{231}Pa (protactinium), was also calculated in the age assessment of the tusk.

The basis for analysis is formed on the assumptions that (1) upon precipitation, carbonate incorporates some uranium but no thorium; (2) the time during which this process occurs is short compared to the age of the sample; (3) the sample subsequently remains a closed system with respect to uranium, thorium, and protactinium isotopes; and (4) the majority of ^{230}Th and ^{231}Pa isotopes in the sample are produced in situ by the uranium incorporated into the sample. Because pedogenic carbonate probably contains various amounts of detrital minerals that are much older than the carbonate matrix, other assumptions made are that (1) if the sample contains any ^{230}Th or ^{232}Th initially, the $^{230}Th/^{232}Th$ ratio will be similar to that of detrital silicate minerals; (2) the ^{238}U, ^{234}U, and ^{230}Th isotopes in the detrital phase are sufficiently old (more than approximately 1 million years) to be in secular equilibrium with each other, and to have not contributed to production of ^{230}Th in the sample during its lifetime; and (3) the thorium isotopes in the detrital minerals are not fractionated during analysis.

4.1.6.2 Means to Assess Accuracy of Results

The derived U-series dates can be compared against age estimates based on the extent of calcic soil development in the deposit, and its height above present stream level. The TL dating technique is also potentially applicable to deposits from which U-series dates may be derived, and therefore could be used in an accuracy evaluation.

4.1.6.3 Results

The dates derived from the U-series analyses are shown in Table 4-15, along with the estimated age of the dated deposit. The probable age reported is for the pedogenic carbonate cemented to the cobble as an indurated rind. The maximum age reported is a "whole rind" date, and the calculation includes any ^{230}Th that may also be present in the sample as noncarbonate detritus.

Table 4-15. Results of Uranium Series Analysis on Paradox Basin Samples

		Age(10^3 yr)				
		$^{234}U/^{238}U$ and $^{230}Th/^{234}U$				
Locality	Sample(a)	Probable	Maximum	$^{230}Th/^{232}Th$	$^{231}Pa/^{235}U$	Estimated(b)
2	Tusk	--	--	43 ± 1	48 ± 4	--
6	Rind	15 ± 1	72 ± 6			ca 75-100
70	Rind	34 ± 3	74 ± 8			ca 210
83	Rind	121 ± 9	121 ± 9			ca 625

(a) Tusk = mammoth (?) tusk
Rind = carbonate rind on gravel clast.

(b) Estimated age is based on height of sampled deposit above present stream level and an assumed long-term incision rate of 0.24 m (0.8 ft) per 1,000 years.

isotopic analysis for the carbonate rind at Locality 83 indicated an anomalously high uranium content, and the correction normally made in the calculations to accommodate the effect of detrital minerals is no longer valid (Ku et al., 1979). However, the $^{230}Th/^{232}Th$ ratio for this sample was much higher than that found in detrital silicate minerals or natural waters, suggesting that most of the ^{230}Th is caused by the in situ decay of uranium. Therefore, the maximum age calculated for the whole sample should be close to the probable time of carbonate deposition (Ku, 1980).

The U-series dates derived from carbonate rinds are consistently much younger than ages estimated or calculated by other means, with the exception of Locality 6, where the maximum U-series date is comparable to that estimated for the deposit on the basis of topographic setting (Table 4-15). The discrepancy cannot be readily explained. The rinds all appeared to have been of adequate quality, so they should have yielded ages that are more similar to those estimated for the deposits by other means (Ku, 1980).

A wide range of dates was acquired by the various attempts to date the mammoth(?) tusk found in Bartlett Wash (Locality 2, Table 1-1). One of the ^{14}C dates (>35,000 years) is on the same order of magnitude as the obtained U-series date of 48,000±4,000 years BP. However, the other ^{14}C date and the amino acid data suggest a much younger age for the tusk; the younger age is probably more accurate for this locality because, since no significant amount of calcic soil development was observed in nearby deposits, they may be early Holocene in age. However, the well-consolidated nature of some of the deposits, which are up to 15 m (50 ft) thick, support an older age interpretation. Further study is needed to resolve the accuracy of the U-series date for the mammoth(?) tusk and the age of the Bartlett Wash deposits.

The preliminary application of U-series analyses as a dating method demonstrates the need to analyze multiple samples from each site in order to evaluate the accuracy of the derived data.

4.1.7 Relative Weathering

Weathering is a process in which minerals that have been formed at high temperatures and pressures attempt to reach equilibrium with their present physical environment on the earth's surface. This environment is usually characterized by ambient climatic conditions and may include other factors, such as the specific chemistry of a soil solution. The extent to which weathering has occurred is therefore a function of the physical environment and the length of time that the object of interest has been exposed to weathering processes.

This premise is the basis for using the extent of weathering as a relative dating technique. Three dating methods have been used in project studies to date: (1) comparison of the thickness of weathering rinds developed in cobbles in fluvial terraces of varying age; (2) comparison of the extent of etching of hornblende and augite mineral grains in soil samples collected from terraces of varying age; and (3) comparison of X-ray diffractograms of quartz, feldspar, and clay minerals to define relative ages of soils and deposits.

Of the three methods, only the X-ray studies provided sufficient distinguishing characteristics to separate soils and/or deposits of varying age. The approach utilizing weathering rinds suffered from the inhomogeneity of the rock clasts both with respect to mineral grain size and mineralogy within the cobbles examined. The heavy mineral suites separated for weathering analysis also exhibited no significant trend in weathering characteristics when they were compared to estimated ages of the sampled deposits.

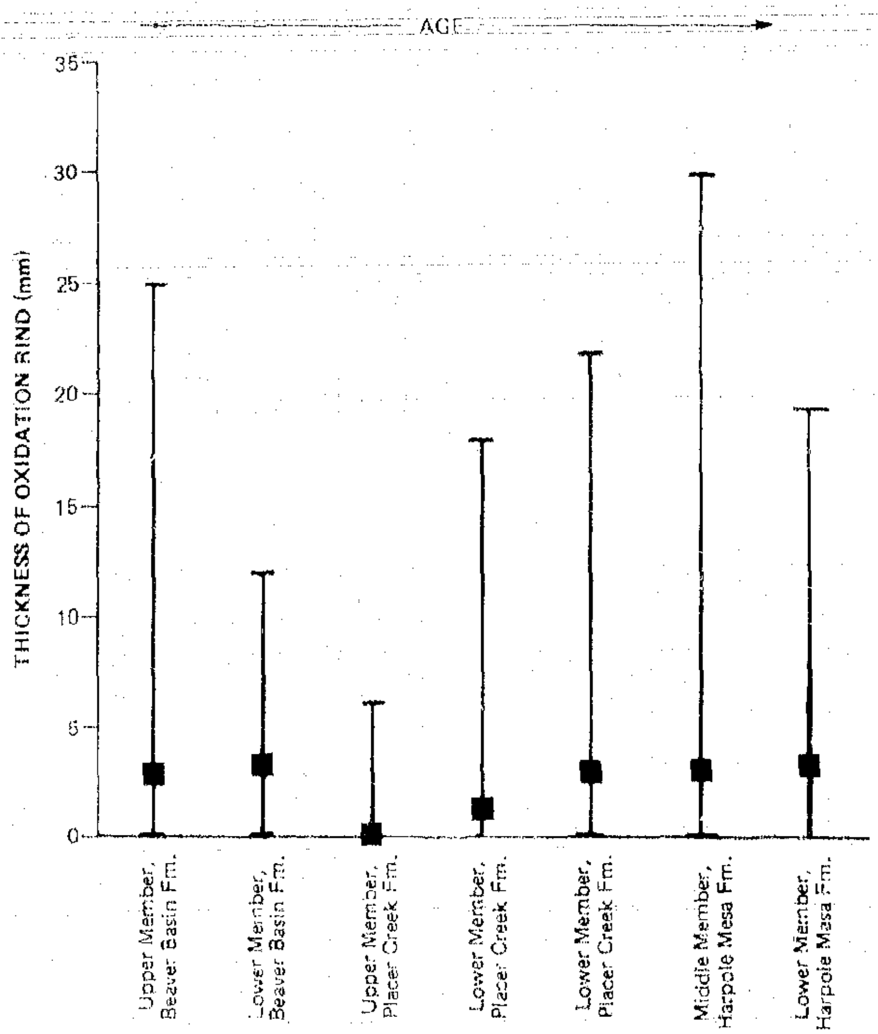
4.1.7.1 Weathering Rind Development

Criteria established by Colman (1979) were used to select gravel clasts for the study of relative thickness of weathering rinds from gravel deposits of varying ages. The selected clasts were of similar lithology and grain size, and were collected from comparable soil horizons in the subsurface. The B soil horizon is the preferred horizon because it is the zone of maximum weathering in the soil profile. However, the B horizon is commonly absent from profiles developed on deposits in southeastern Utah, so relative rind thicknesses were compared on clasts collected from the C soil horizon. Collection of clasts from the ground surface was avoided because of uncertainty regarding the length of time the clasts had been exposed on the ground surface, and the effect that such exposure may have had on the rate at which the oxidation rinds developed.

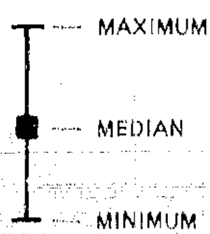
Igneous cobbles were collected from backhoe soil pits excavated in a series of fluvial terraces in the Spanish Valley correlation area south of Moab, and in the Gibson Dome area. At least 25 cobbles were measured at each locality. The results of the weathering rind studies and concurrent soil studies undertaken at these locations are described in WCC (1982a, Vols. I and II, respectively) and are summarized below.

Igneous cobbles from the La Sal Mountains were collected from the Beaver Basin, Placer Creek, and Harpole Mesa deposits in Spanish Valley (Table 1-1). The projected age of these gravels ranges from late to early Pleistocene. Measurements of oxidation rinds developed on the cobbles revealed no consistent trends with increasing age of the deposit (Figure 4-8). Variability in lithology, spalling of the outer surfaces of clasts, and deceleration of weathering caused by carbonate accumulation on the clasts are probably responsible for the lack of progressive oxidation rind development with age of the deposit. In addition, the variable truncation of soil horizons on successive terraces made it difficult to compare the weathering histories of buried clasts.

Igneous cobbles derived from the Abajo Mountains were collected from the B or Cca soil horizons exposed in backhoe soil pits excavated into Indian Creek terraces in the Gibson Dome area (Localities 32 to 39). Despite a general increase in rind thickness with terrace height above present stream level, the relative ages of the terraces could not be consistently defined using this technique (WCC, 1982a, Vol. II, p. 4-9) (Figure 4-9). The similarity in rind development on topographically dissimilar terraces may reflect the roughly equivalent ages of the deposits and/or spalling from the clast surfaces.



Note:
Oxidation rinds developed on igneous cobbles, derived from the La Sal Mountains, in terrace deposits in Spanish Valley. Formations were initially described by Richmond (1962). At least 25 clasts were measured at each locality.



LOG 1586
REV. 1—2/9/83

OXIDATION RINDS, SPANISH VALLEY

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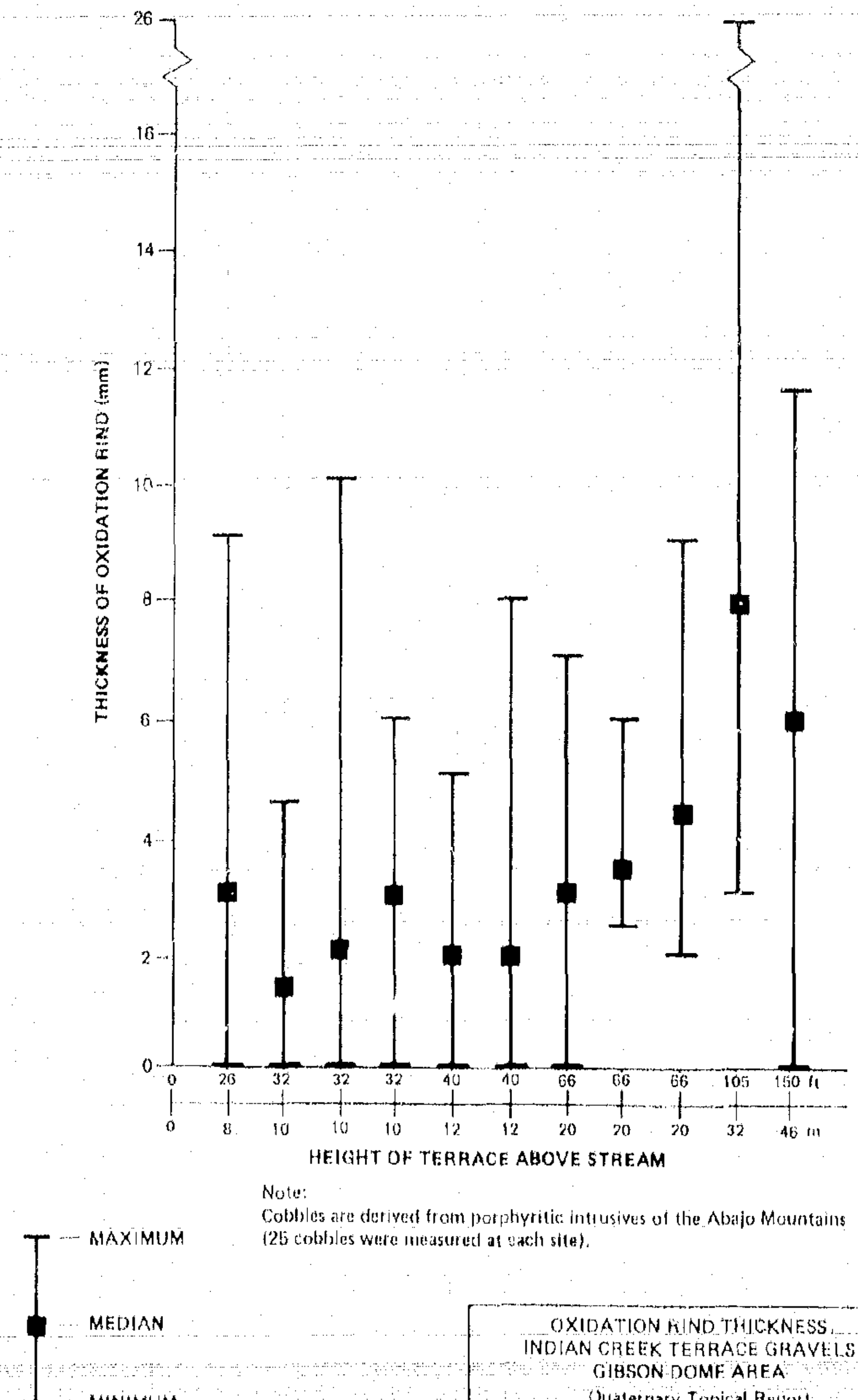
Figure 4—8



Note:
Cobbles are derived from porphyritic intrusives of the Abajo Mountains (25 cobbles were measured at each site).

LOG 1587
REV.1—1/13/82

OXIDATION RIND THICKNESS,
INDIAN CREEK TERRACE GRAVELS
GIBSON DOME AREA
Quaternary Topical Report

Project No. 17000
Woodward-Clyde Consultants

Figure 4-9

No further attempts to use weathering rind thickness as a dating method were made in the Paradox Basin studies.

4.1.7.2 Heavy Mineral Etching

Etching is a pedogenic or diagenetic process that involves progressive solution of detrital mineral grains. Preferred solution parallel to the cleavage direction of chain silicates (especially pyroxenes and amphiboles) creates distinctive, serrated shapes that become more irregular with time. Eventually, selective dissolution depletes the less resis' minerals.

Recent studies of heavy mineral etching in soils hav established its use as a relative age indicator for Quaternary deposits in several areas of the western United States (Crone, 1972; La Fleur, 1972; Shroba, 1972; Gillam et al., 1977) and in the Canadian Arctic (Locke, 1976). These studies have concentrated on etching of augite, diopside, hypersthene, and hornblende, and have established susceptibility sequences for several other minerals.

Etching rates vary with individual minerals, local precipitation, position in the soil profile, and the character of the soil environment. In subhumid regions, maximum etching usually occurs in B horizons (Crone, 1972), especially in older soils. Shroba (1972) suggested that etching rates increase with clay buildup, but La Fleur (1972) concluded that etching rates decrease with time, particularly in arid regions. Crone (1972) attributed decreasing etching rates in K soil horizons to the protective role of carbonate cement. In general, etching increases with parent material age in all areas studied except near Reno, Nevada (La Fleur, 1972), where annual precipitation is relatively low (170 mm [7 in]). Precipitation is also low in the Canadian Arctic, but may be more effective as a weathering agent than at Reno because of low temperatures.

4.1.7.2.1 <u>Sample-Collection Sites.</u> A feasibility study was undertaken for this project to further assess the value of mineral etching as an age indicator in soils from arid and semiarid regions of the southwestern United States. Etching was evaluated for augite and hornblende separated from samples collected at 10 sites in four areas discussed in Sections 4.1.7.2.1.1 through 4.1.7.2.1.4. These areas are (1) alluvial fans flanking the La Sal Mountains near Spanish Valley, (2) alluvial fans in the Abajo Mountains, (3) the Elk Ridge area of southeastern Utah, and (4) the Animas River area in western Colorado and New Mexico (Table 1-1, Figure 1-1). Mean annual precipitation is similar in the four areas, ranging approximately from 200 mm (8 in) in the lowlands to 500 mm (20 in) in the mountains. The samples were collected from relict, composite, and compound soil profiles developed on loess, alluvial sand, and alluvial gravel deposits that range from Holocene to early Pleistocene in age.

Sites were selected and sampled during reconnaissance investigations in 1979. Because better age control (based on a combination of glacial correlations, tephrochronology, magnetostratigraphy, and radiometric dating) was available for deposits in the La Sal (Spanish Valley) and Animas River areas, samples from these areas were expected to yield rates of etching that could be used to estimate the age of deposits in the other areas.

4.1.7.2.1.1 La Sal Mountains area. Samples were collected from three sites in Spanish Valley and on the southwestern flank of the La Sal Mountains. Gravel clasts in deposits at these sites are derived from the La Sal Mountains and consist of porphyritic intrusive rocks and minor sedimentary lithologies. At Site 1 (Profile 1, Figure 4-10; Locality 7, Figure 1-1), two buried soils are developed in Holocene sandy alluvium and loess deposits. Detrital charcoal from the lowest unit at this site yielded a radiocarbon date of 1,280±55 years BP (Table 4-6).

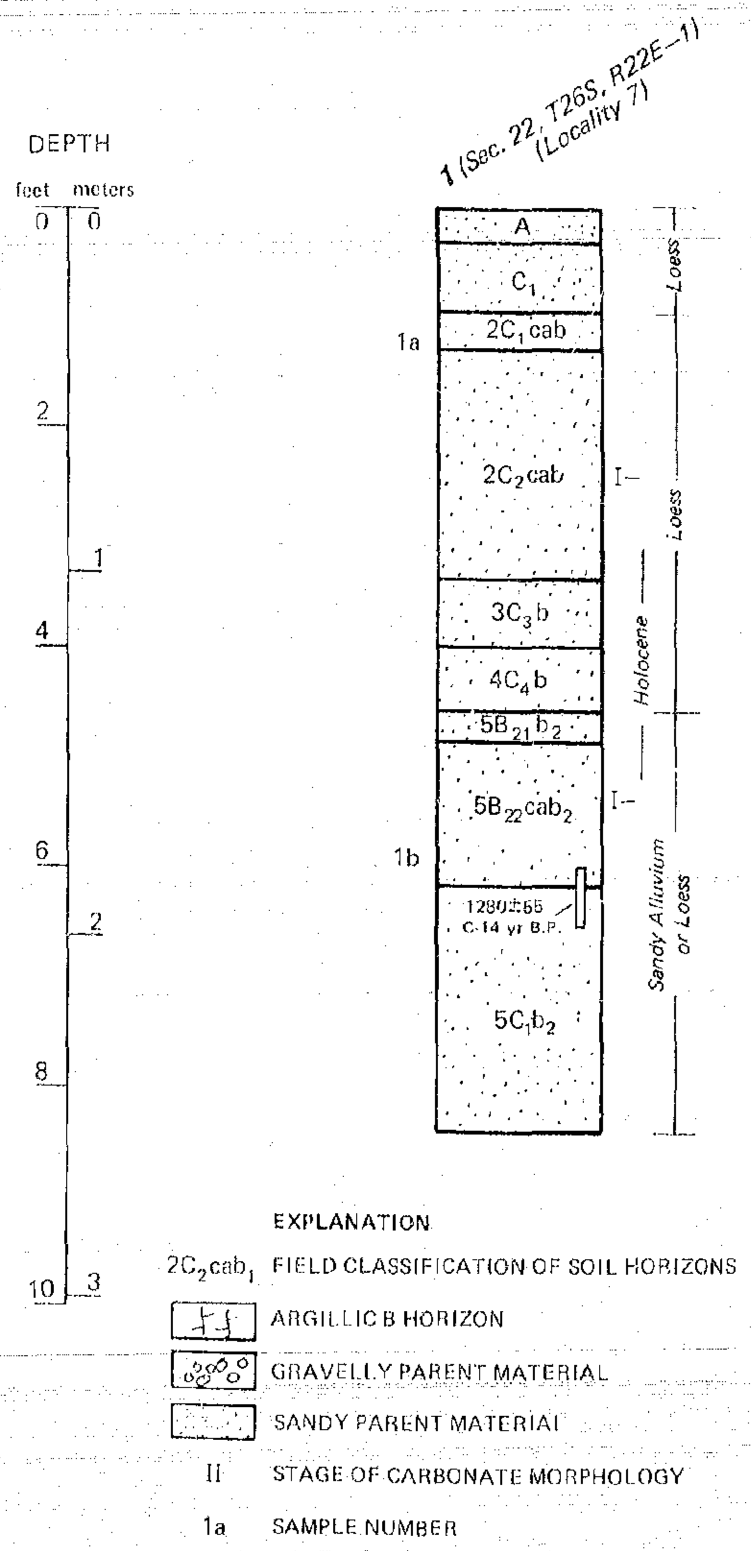
The section exposed at Site 2 (Profile 2, Figure 4-10; Locality 23, Figure 1-1) consists of a sequence of three fine-grained alluvial units overlying alluvial fan gravel. Richmond (1962) mapped the lower gravel unit as Placer Creek Formation, and the two overlying fine-grained units as Beaver Basin Formation.

At Site 3 (Profile 3, Figure 4-10; Locality 6, Figure 1-1) a moderately well-developed soil consisting of a textural B horizon overlying a Stage II to III carbonate horizon is formed in loess and underlying fluvial terrace gravels mapped as Placer Creek Formation by Richmond (1962). U-series dating of caliche rinds in the gravel unit yielded a probable age of 15,000±1,000 years BP to a maximum age of 72,000±6,000 years BP. Based on soil development and the topographic position of the deposit, it appears that the maximum date more accurately reflects the age of this deposit (Section 4.1.6.3). Similarly, measurement of the pedogenic carbonate accumulated in the soil profile yielded an age estimate of 245,000 to 405,000 years, which is judged to be too old because the terrace is only 18 to 24 m (60 to 80 ft) above present stream level (Section 4.2.1.1.2).

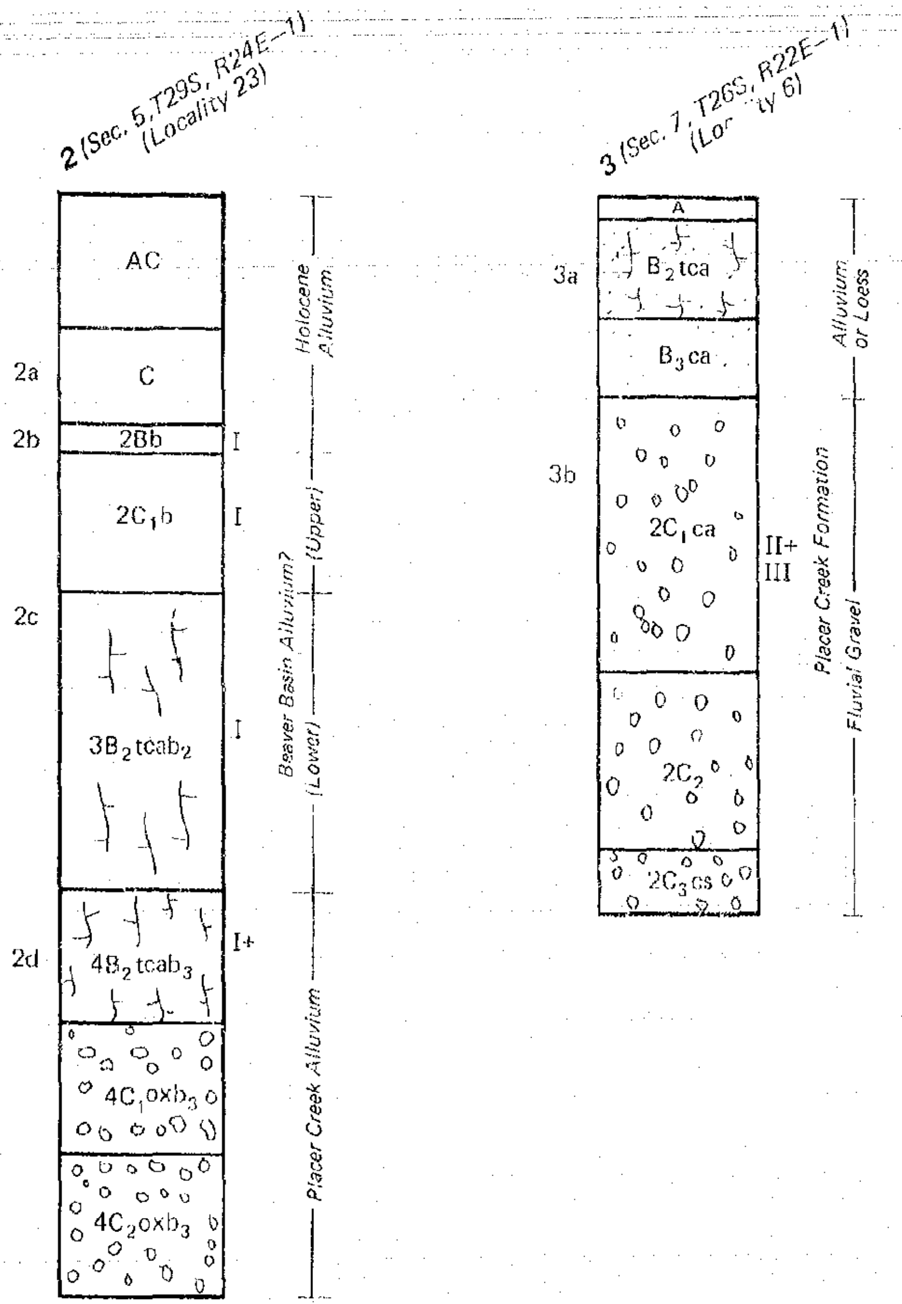
4.1.7.2.1.2 Animas River area. Deposits of loess and alluvium overlying alluvial sand and gravel were sampled at three sites along the Animas and San Juan Rivers in southwestern Colorado and northwestern New Mexico (Localities 84, 85, and 86, Table 1-1, Figure 1-1). The estimated ages of the deposits range from Holocene to mid-Pleistocene. Although this area lies outside the Paradox Basin study area, it was selected as an area where a regional etching rate could be established because a wide age range of terraces is present.

In Profile 4 (Figure 4-11; Locality 84, Figure 1-1), a buried soil having an argillic B horizon and Stage I carbonate is developed on alluvial sand estimated to be equivalent in age to late Bull Lake deposits (approximately 200,000 to 130,000 years BP), based on terrace height and correlation with glacial moraines upstream. Because a slight erosional slope exists at this site, the buried soil may not represent maximal soil development. The buried soil is overlain by colluvium with a weak relict soil and a Stage II carbonate morphology.

In Profile 5 (Figure 4-11; Locality 85, Figure 1-1), the buried soil is developed on gravel that is estimated to be pre-Bull Lake equivalent in age on the basis of terrace height, and displays Stage III carbonate morphology. This soil has been truncated and buried by loess. The relict soil developed on the loess displays an argillic B horizon and Cca horizon with Stage II carbonate morphology. Profile 6 (Figure 4-11; Locality 86, Figure 1-1) exposes loess underlain by a fining-upward sequence of gravel and sandy



DEPTH
feet
meters
0
2
4
6
8
10
0
1
2
3
1 (Sec. 22, T26S, R22E–1)
(Locality 7)
A
C1
2C1cab
1a
2C2cab
I–
3C3b
4C4b
5B21b2
5B22cab2
I–
1b
1280±65
C-14 yr B.P.
5C1b2
Loess
Loess
Holocene
Sandy Alluvium
or Loess
EXPLANATION
2C2cab1 FIELD CLASSIFICATION OF SOIL HORIZONS
ARGILLIC B HORIZON
GRAVELLY PARENT MATERIAL
SANDY PARENT MATERIAL
II STAGE OF CARBONATE MORPHOLOGY
1a SAMPLE NUMBER



NOTE: LOCATIONS OF SOIL PROFILES ARE SHOWN ON FIGURE 1–1

SOIL PROFILES
LA SAL MOUNTAINS AREA

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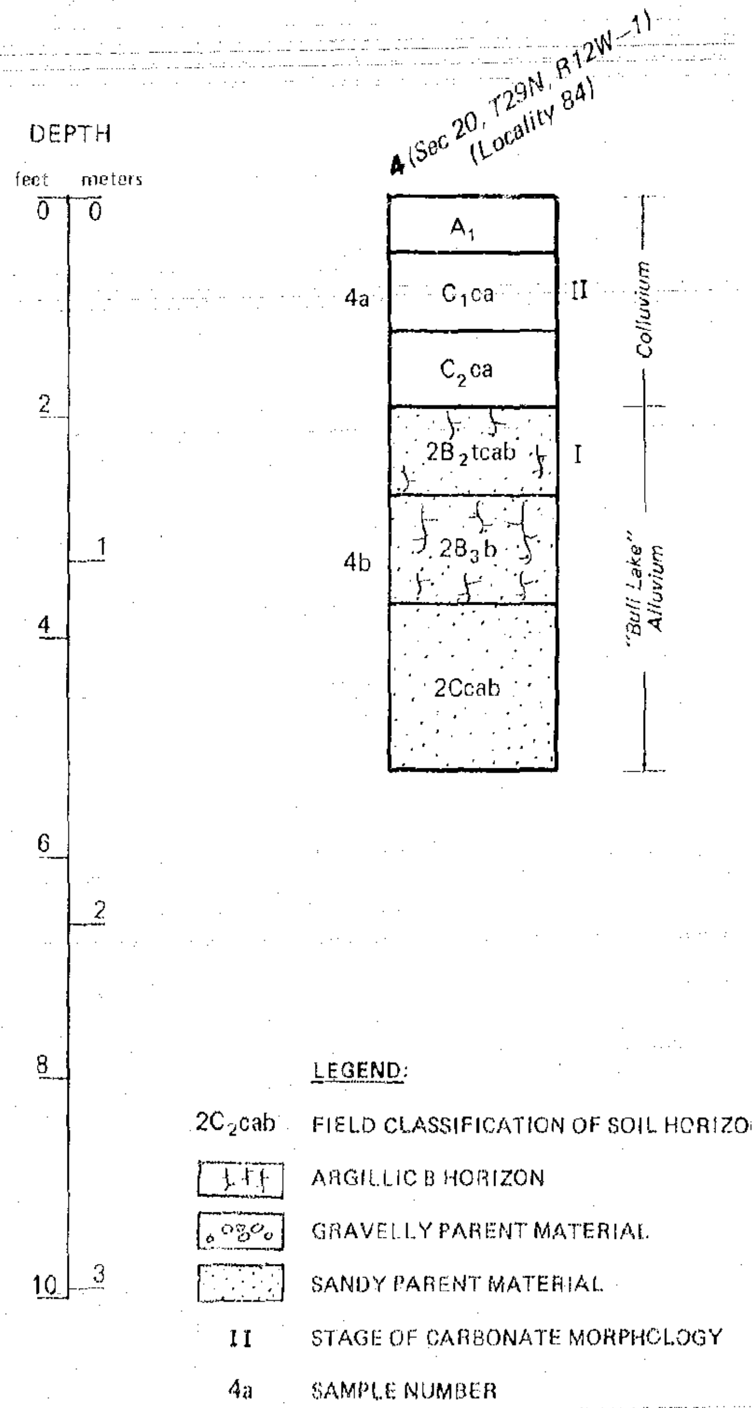
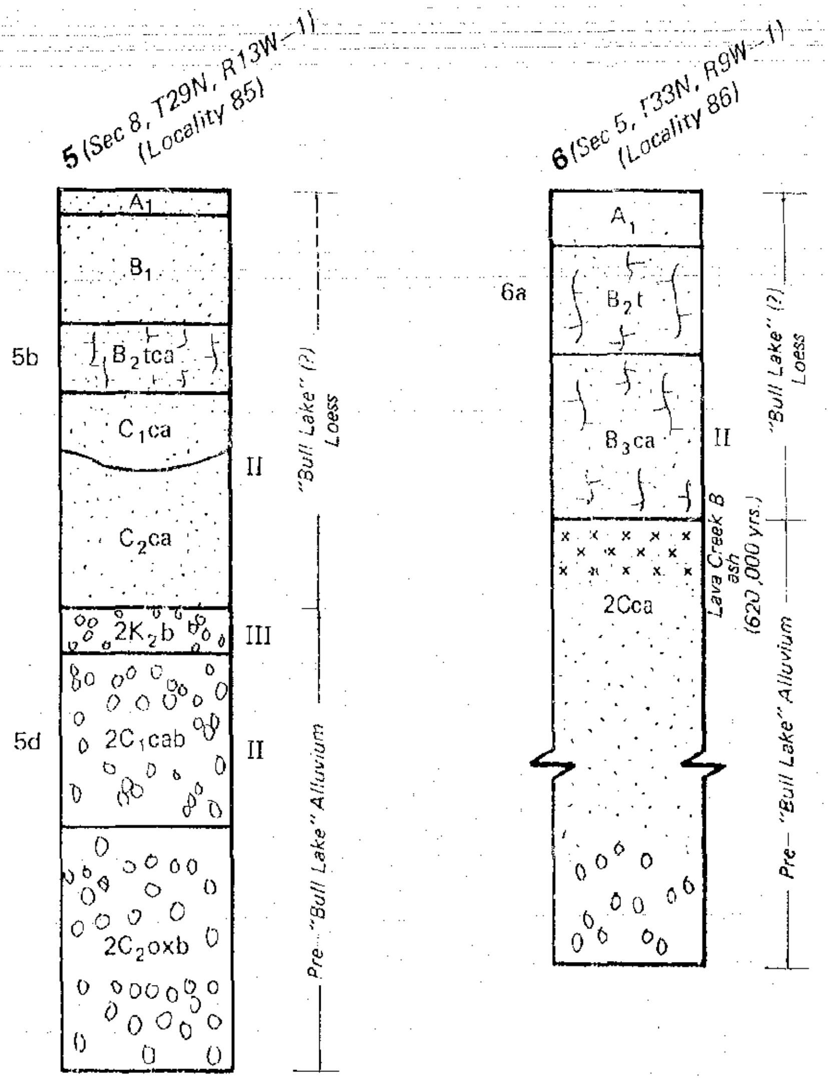


NOTE: LOCATIONS OF SOIL PROFILES ARE SHOW



ORIZON

OGY

SHOWN ON FIGURE 1–1

SOIL PROFILES,
ANIMAS RIVER/SAN JUAN RIVER

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Figure 4–11

alluvium. Lava Creek B (Pearlette "O") ash (approximately 620,000 years old [Gillam et al., 1985; Izett and Wilcox, 1982]) is exposed in the upper part of the alluvium. The relict soil developed on these deposits contains an argillic B horizon and a Cca horizon with Stage II carbonate morphology.

4.1.7.2.1.3 Abajo Mountain area. Samples for heavy mineral analysis were analyzed from one site near Blanding, on the eastern flank of the Abajo Mountains area. Deposits at this site (Profile 7, Figure 4-12; Locality 54, Figure 1-1) consist of loess capping alluvial fan gravel, which, based on paleomagnetic data (Section 4.1.5), is estimated to have been deposited before 0.73 million years ago. Soils developed on the overlying loess are estimated to be at least equivalent in ages to those on Bull Lake deposits. Gravel in this deposit consists predominantly of igneous lithologies from the Abajo Mountains and a few sedimentary clasts.

4.1.7.2.1.4 Elk Ridge area. Samples were collected at two sites (Localities 69 and 80, Figure 1-1) along Cottonwood Wash in the Elk Ridge area where alluvial terrace deposits of probable Pinedale equivalent age (approximately 130,000 to 10,000 years BP; Table 4-16), based on terrace height and soil profile development, are overlain by Holocene loess. Gravel clasts in these deposits consist of porphyritic intrusive rock from the Abajo Mountains, and various sedimentary lithologies. Soil profiles (Profiles 8 and 9) for these sites are shown on Figure 4-12.

4.1.7.2.2 Laboratory Procedures. The procedures used in sample preparation and analysis for the heavy mineral etching dating method are described in WCC (1980). Because previous studies have shown that etching is usually greatest in B soil horizons (La Fleur, 1972; Gillam et al., 1977), samples from these horizons were examined in this study wherever possible. If a B horizon was absent because of immaturity or truncation of the soil, the A and/or C horizons were examined. Mineral grains from the C and A horizons were also examined to assess etching at greater depths in the soil profile and the possible recycling of etched grains from one deposit to another.

The degree of hornblende and augite etching was assessed using the following two different methods:

1. Subjective assignment of etching class ("loose grain method"). Loose grains from the nonmagnetic heavy mineral fraction of each sample were examined under a binocular microscope, and etching assignments were based on a 5-class visual scale of overall grain shape and relative length of etching terminations (Gillam et al., 1977). A similar technique based on a 10-class scale was used by Shroba (1972) and La Fleur (1972).

2. Measurement of maximum etching depth. The nonmagnetic heavy mineral fraction of each sample was permanently mounted on a glass slide, and maximum etching depth was measured in 4-μ increments using an ocular micrometer. Locke (1976) developed this procedure using 6.5-μ increments.

Table 4-16. Correlation of Quaternary Deposits in the Paradox Basin Area

Age (years)	Geologic Era and Epoch[1]		Polarity Epoch[1]	Rocky Mountain Region[2]	NE Arizona and NW New Mexico[3]	Paradox Basin, Southeast Utah: Green River Area[4]	Paradox Basin, Southeast Utah: Spanish Valley Area[4,5]	Paradox Basin, Southeast Utah: Gibson Dome Area[4]
0 – 5,000 – 10,000	QUATERNARY	HOLOCENE	BRUNHES (normal)	Holocene	Naha Fm Tsegi Fm	Dunes of San Rafael Desert, floodplain and channel deposits	Goid Basin Fm	Fine-grained alluvial fill showing multiple cut/fill episodes
10,000 – 50,000 – 100,000	QUATERNARY	PLEISTOCENE, late	BRUNHES (normal)	Late Pinedale Early Pinedale	Jeddito Fm Late Wupatki "gravelly sand"	Gravel terraces of Green and San Rafael rivers	Beaver Basin Fm	Lower gravel terraces of Indian Creek and other drainages Higher gravel terraces of Indian Creek and other drainages
150,000 – 200,000 – 500,000 – 700,000	QUATERNARY	PLEISTOCENE, middle	BRUNHES (normal)	Bull Lake Pre-Bull Lake	Early Wupatki	?	Placer Creek Fm Upper Member, Harpole Mesa Fm Middle Member Harpole Mesa Fm	High terraces of Cottonwood Wash ?
1,000,000	QUATERNARY	PLEISTOCENE, early	MATUYAMA (reversed)		Late Black Point	? Alluvium of older pediments and Green River terraces	Lower Member, Harpole Mesa Fm	Fanglomerates and loess deposits on surfaces flanking Abajo Mountains ?
2,000,000	TERTIARY	PLIOCENE	← MATUYAMA GAUSS (normal)		Early Black Point	?		? "Suicide Gravels"

LEGEND:

1. From Bloom (1978) and Bowen (1978).

2. Modified from Meierding and Birkeland (1980).

   Previous workers (Richmond, 1965, for example) considered the Bull Lake Glaciation to have occurred before about 100,000 years BP.

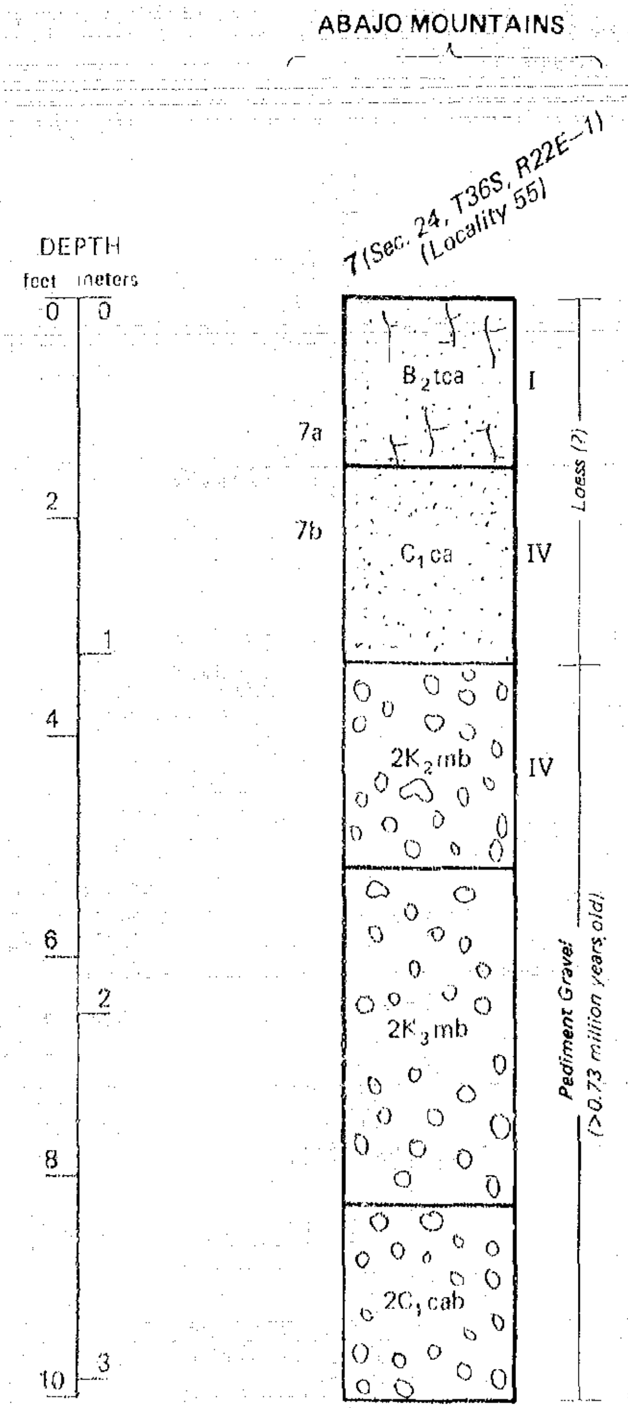
   Recently, evidence provided by relative dating data (Meierding, 1977; Madole and Shroba, 1979), by obsidian hydration dating (Pierce et al., 1976), and by uranium-trend dating (Shroba et al., 1983) suggest that the Bull Lake Glaciation correlates with the worldwide climatic event recorded in deep-sea cores about 130,000 to 150,000 years BP (Shackleton and Opdyke, 1973).

3. Modified from Hack (1942), Cooley et al. (1969) and O'Sullivan et al. (1979). "Gravelly sand" is thought to be "pre-Pinedale" in age (O'Sullivan et al., 1979).

4. Recent and older eolian deposits blanket most surfaces in the Paradox Basin. At several localities, multiple episodes of deposition have occurred. Colluvial deposits of varying ages are also widespread on slopes of the areas.

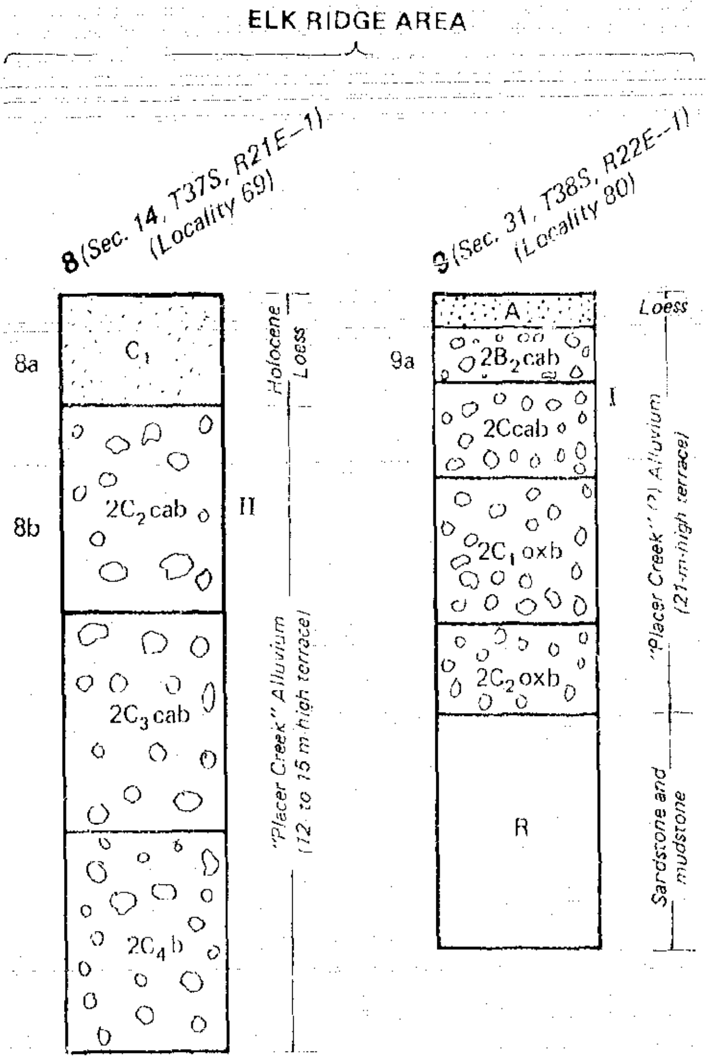
5. The correlation of the La Sal Mountain deposits with Rocky Mountain glacial deposits was made on the basis of the earlier chronology (Richmond, 1962). Based on observations of rock weathering and soil development in Spanish Valley, it appears that Placer Creek deposits significantly predate those of the Beaver Basin Formation.

LOC 1705
REV. 2-9/30/85



ABAJO MOUNTAINS
7 (Sec. 24, T36S, R22E—1)
(Locality 55)
DEPTH
feet
meters
0
2
4
6
8
10
0
1
2
3
7a
7b
B2tca
C1ca
2K2mb
2K3mb
2C1cab
I
IV
IV
Loess (?)
Pediment Gravel
(>0.73 million years old)

LOG 1590



LEGEND:

$2C_2cab_2$ FIELD CLASSIFICATION OF SOIL HORIZONS

ARGILLIC B HORIZONS

GRAVELLY PARENT MATERIAL

SANDY PARENT MATERIAL

II STAGE OF CARBONATE MORPHOLOGY

1a SAMPLE NUMBER

NOTE: LOCATIONS OF SOIL PROFILES ARE SHOWN ON FIGURE 1–1.

SOIL PROFILES,
ABAJO MOUNTAIN/ELK RIDGE AREA

Quaternary Topical Report

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During examination of the permanent grain mounts, it was noted that grinding involved in preparation of the permanent glass slides had altered the appearance of etching terminations in some samples. Therefore, the maximum etching depth was also measured for selected samples using temporary oil mounts. Because of time constraints, this procedure was limited primarily to samples from the La Sal Mountains area, which were considered to represent the best potential for demonstrating progressive etching with increasing relative age.

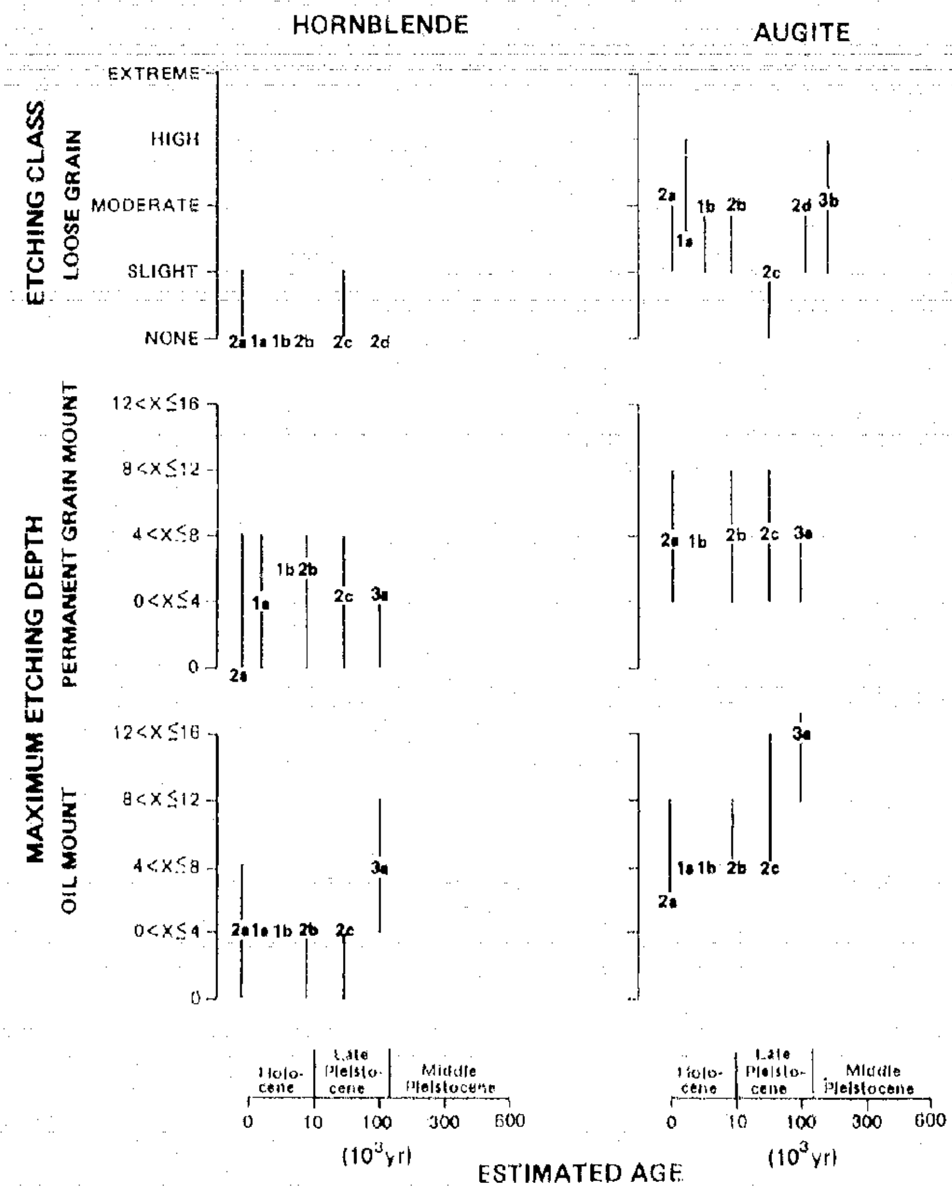
4.1.7.2.3 Results. Graphs showing etching versus relative age are presented on Figures 4-13 through 4-15. Samples from the Animas River and La Sal Mountains provided the most useful data because augite was virtually absent in samples from the Abajo Mountains and adjacent Elk Ridge areas. Although this absence may reflect the small size of some of these samples, it is more likely that augite is simply absent in the source area. It was not possible to analyze the smaller samples using both the etching class and maximum etching depth methods.

As expected because of work done in other regions, the modal class of augite etching nearly always exceeded the modal class of hornblende etching, although the etching ranges for the 16th to 84th percentiles commonly overlapped (Figures 4-13 and 4-14). By the loose grain method, maximum hornblende etching was slight and most samples displayed no etching, whereas augite etching was slight or moderate. By the permanent and oil mount methods, hornblende etching generally ranged from 0 to 4 μ, but sometimes reached a depth of 8 μ. Augite etching was usually 8 μ or less, but one sample displayed an etching depth of 16 μ.

Etching increased slightly with the relative age of deposits only in the Animas River area. Modal hornblende etching is slight (between 0 and 4 μ) in Sample 6a (Figure 4-14) from loess overlying the approximately 610,000-year-old Lava Creek ash deposit (Profile 6, Figure 4-11), compared with the slight etching in deposits approximately 500,000 years old from the Colorado Front Range (Crone, 1972), and the roughly 3.5 μ-mean-maximum etching depth in pre-Wisconsinan (pre-Pinedale ?) samples from the Canadian Arctic (Locke, 1976).

Modal augite etching in the same sample is moderate, between 4 and 8 μ. This is a low value compared to previous data for pre-Wisconsinan soils (12.5 μ for a sample collected east of Reno, Nevada [La Fleur, 1972]; 20 μ at Wallowa Lake, Oregon [Shroba, 1972]; and 35 μ in the eastern Sierra Nevada [La Fleur, 1972]).

In samples from the La Sal and Abajo Mountains areas, neither mineral displays trends with age when etching is measured by the loose grain or permanent mount methods (Figures 4-13 and 4-15). However, the oil-mount data display weak trends for both minerals; the best trend was observed for augite etching in a series of stacked soils in Profile 2 of the La Sal Mountains area (Figure 4-13). The similar modal etching displayed by the surface soil (Sample 2a) and the buried soils developed on older deposits (Samples 2c and 2d) in this same section suggest that some etched grains were recycled from older soils. Recycling is likely, considering that the fine-grained fill deposits in channels on the fan at this site are probably derived in large part from nearby Placer Creek deposits, which mantle most of the fan.

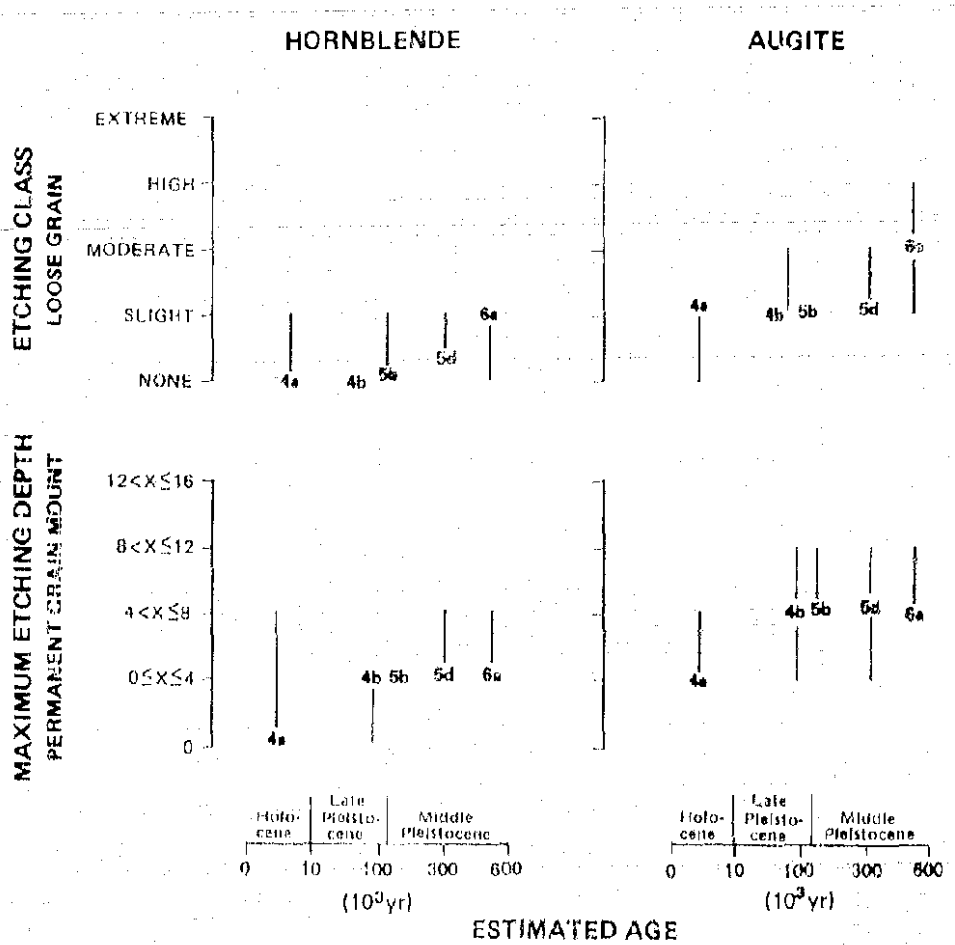


LEGEND:

2a SAMPLE NUMBER. LOCATIONS OF SAMPLES ARE SHOWN IN FIGURE 4-10.

NOTE: SAMPLE NUMBER IS PLOTTED AT MODAL ETCHING CLASS; VERTICAL BAR SHOWS CLASSES CONTAINING 16th AND 84th PERCENTILES, IF DIFFERENT.

LOG 1591 REV. 0–8/25/83	DEGREE OF ETCHING VERSUS RELATIVE AGE, LA SAL MOUNTAINS AREA Quaternary Topical Report	
	Project No. 17000 **Woodward-Clyde Consultants**	Figure 4–13

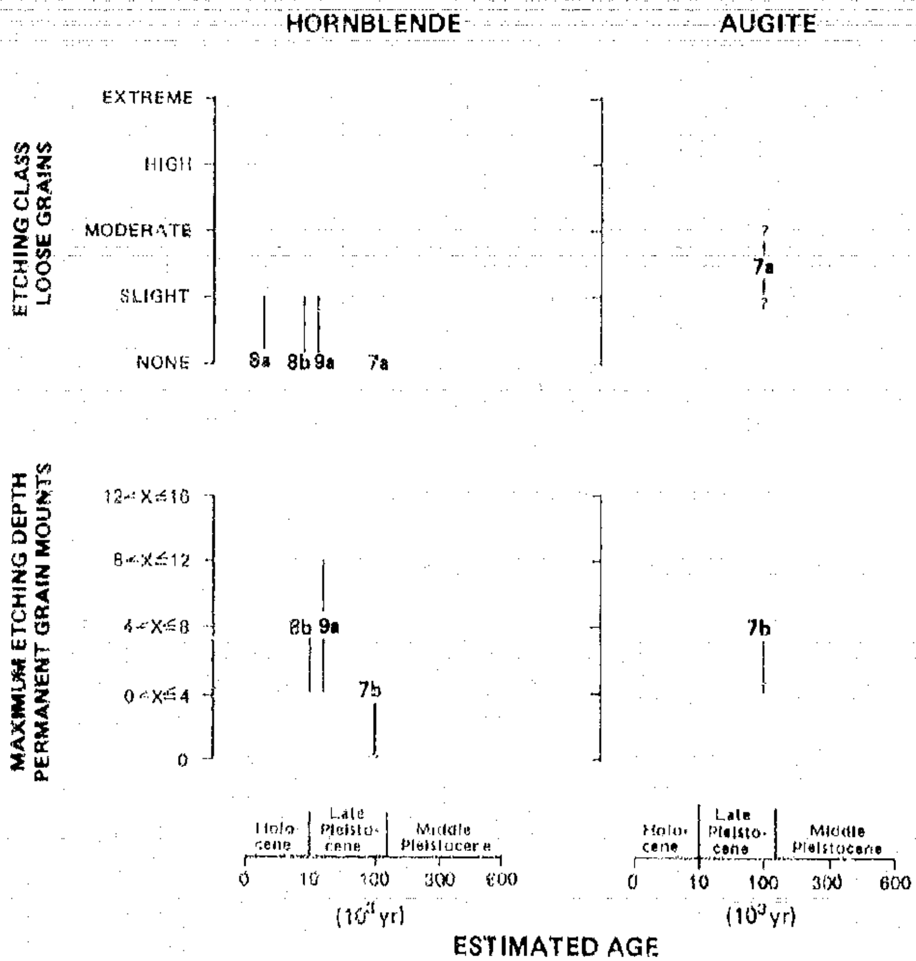


LEGEND:

4a SAMPLE NUMBER. LOCATIONS OF SAMPLES ARE SHOWN IN FIGURE 4–11.

NOTE: SAMPLE NUMBER IS PLOTTED AT MODAL ETCHING CLASS; VERTICAL BAR SHOWS CLASSES CONTAINING 16th AND 84th PERCENTILES, IF DIFFERENT.

LOG 1592 REV. 0—8/25/83	DEGREE OF ETCHING VERSUS RELATIVE AGE, ANIMAS RIVER Quaternary Topical Report	
	Project No. 17000 Woodward-Clyde Consultants	Figure 4–14



LEGEND:

8b SAMPLE NUMBER. LOCATIONS OF SAMPLES ARE SHOWN IN FIGURE 4–12.

NOTE: SAMPLE NUMBER IS PLOTTED AT MODAL ETCHING CLASS; VERTICAL BAR SHOWS CLASSES CONTAINING 16th AND 84th PERCENTILES, IF DIFFERENT.

DEGREE OF ETCHING
VERSUS RELATIVE AGE,
ABAJO AND ELK RIDGE AREAS

Quaternary Topical Report

LOG 1593
REV. 0–8/25/83

Project No. 17000
Woodward-Clyde Consultants

Figure 4–15

Statistical analysis of the etching data for the Animas River and La Sal Mountains areas indicates that a sufficient number of grains per sample were measured to rule out the possibility that the poor trends with age were the result of statistical variability between grains measured in each sample.

4.1.7.2.4 Summary. The poor trends of mineral etching with age for samples from the Animas River and La Sal Mountains areas are attributed primarily to the low level of precipitation (approximately 200 mm [8 in] per year at most sites), which has retarded differential etching with respect to age and pedologic factors. A protective coating of pedogenic carbonate on mineral grains could also retard the etching process. In addition, uncertainties in relative age estimates, different weathering histories for buried and relict soils on parent materials of similar age, and recycling of etched grains probably contributed to the poor trends exhibited by the La Sal Mountains samples. Although the data for the Abajo Mountains and Elk Ridge areas were insufficient to evaluate possible age trends, the apparent rates of etching appeared comparable to those measured for the Animas River and La Sal Mountains areas.

Because of the apparently slow rates of etching in the four areas studied and the apparent paucity of augite in source rocks from the Abajo Mountains, further evaluation or use of this method as a relative dating technique in southeastern Utah is not justified.

4.1.7.3 X-Ray Analysis

X-ray diffraction patterns of minerals in pedogenic units have been used to define and distinguish Quaternary soils and/or deposits of different ages (Isherwood, 1975; Markos, 1977; Harpster, 1981). Like weathering rind development and heavy mineral etching, this method is based on the premise that the structure of minerals within a soil changes toward equilibrium with the soil solution, and that the extent to which this equilibrium condition is met is time dependent.

Previous investigators have utilized (1) normalized ratios of the height of specific feldspar (F) and quartz (Q) peaks of X-ray diffractograms (Isherwood, 1975; Markos, 1977); and (2) diffractogram patterns of clay minerals (Harpster, 1981) to establish relative ages of Quaternary deposits.

Isherwood (1975) demonstrated a constant increase in F/Q weathering ratios with depth in the majority of the Arctic soil profiles that she examined, in deposits ranging in age from pre-Wisconsinan to Neoglacial. Similarly, Berry (1984) found a progressive trend in weathering ratios with age for soil associations (catenas) developed in glacial moraines in Idaho, where average precipitation is 90 cm (35 in) and average temperature is 2°C (35.6°F).

An alternative use of X-ray diffraction data collected from pedogenic horizons is suggested by Harpster (1981). In an examination of clay patterns, Harpster is able to see distinctive changes in reflection spacing, and in the intensity and shape of individual mineral peaks when the patterns are stacked.

to correspond to depth below ground surface. These changes correspond either to changes in the parent material or to pedogenic subdivisions.

Glycolated and heat-treated clay mounts are the most sensitive and useful of the X-ray analytical techniques for these studies. However, only the silt-size fraction was separated for the X-ray analysis, so the clay minerals were theoretically not included in the retained sample fraction. Therefore, although comparison of X-ray diffraction patterns had not previously been applied to quartz and plagioclase X-ray data, the X-ray patterns run by Coors Spectrochemical Laboratory in Golden, Colorado, for the P/Q weathering ratios were examined to assess whether these two minerals exhibit distinctive changes comparable to those previously reported for clay minerals in soil profiles.

4.1.7.3.1 Sampling Procedures. The silt-size fraction was separated from soil samples of specified horizons following particle size analyses in the laboratory. The selected samples were from the B soil horizons, where weathering should be maximized; from the uppermost C or K horizons, where the B horizon had been removed by erosion; and from the basal soil units, which were considered representative of the parent material. Because the original samples were collected for pedogenic studies (such as those reported in Section 4.1.1), they were composite or trench samples that incorporated as much as 20 vertical cm (8 in) of the soil horizon.

4.1.7.3.2 Laboratory and Analytical Procedures. Laboratory methods used to derive P/Q weathering ratios for this project were developed from those utilized by Isherwood (1975) and Markos (1977). The silt samples were initially X-rayed by Coors Spectrochemical Laboratory in Golden, Colorado. The samples were split into triplicate subsamples at the laboratory. Triplicate runs were therefore made for each sample to address potential peak height variability caused by grain orientation during measurement, or by sample preparation. Diffractograms were produced for each subsample for the span between 18 and 32 degrees 2θ. Following examination of the data, another split of the same silt-size samples was run at the WCC Core Facility in Denver, Colorado, in order to obtain the diffraction peaks between 2 and 32 degrees 2θ for each sample. Clay mounts were also made from the silt-size samples from six sites to evaluate whether sufficient clay minerals remained in the samples to produce diffraction patterns suitable for evaluation. The clay mounts were not glycolated or heat-treated. Clay peaks at 7, 9, and 13 angstroms were examined.

Analysis of quartz and feldspar X-ray patterns involves measurement of the intensity of prominent peaks of both minerals. The intensity value is a linear measurement of the height of the diffraction peak minus the background. The calculation of the weathering ratio (P/Q) of Isherwood (1975) and Markos (1977) uses the intensity of the quartz (Q) peak at 20.8 degrees 2θ, and the feldspar (P) peak at 28.0 degrees 2θ. During analysis of the Coors diffractograms, the two or three most similar feldspar/quartz ratios for each sample were averaged to calculate the P/Q value for a soil horizon.

In the comparison of X-ray diffraction patterns, as reported by Harpster (1981), the X-ray patterns were stacked by depth and labeled with the pedogenic horizon nomenclature recorded on the soil profile log, or determined from laboratory analyses. The reflection spacing and the shape and intensity of specific diffraction peaks were noted, and the following seven X-ray peaks were selected to characterize the sample patterns: quartz at 4.24A; plagioclase at 3.19A, 3.674A, and 4.03A; orthoclase at 3.788A and 3.871A; and illite at 4.49A. Intensity values for these peaks versus depth were plotted for each locality.

4.1.7.3.3. Reproducibility of X-ray Data. Reproducibility of the laboratory data was evaluated by comparing each plagioclase and quartz peak height measurement of a triplicate subset with the mean peak height calculated for that sample for the respective minerals. Peak height values for plagioclase were within 10 percent of the mean for 35 percent of the samples, and within 20 percent of the mean for 67 percent of the samples. For the quartz measurements, 61 percent of the measurements were within 10 percent of the mean calculated for each sample, and 84 percent were within 20 percent. Maximum difference for plagioclase measurements was 78 percent, whereas the maximum difference for the quartz data was 42 percent.

This analysis demonstrates the variability in the X-ray data, particularly for the plagioclase peak that was used in the weathering ratio. Incorporation of the potential error range of these data into the calculation of the weathering ratios for a soil profile improves the results for individual soil profiles.

4.1.7.3.4 Results. The X-ray diffraction data were used to derive P/Q weathering ratios, and to compare diffractogram patterns as a correlation and relative dating method.

4.1.7.3.4.1 P/Q weathering ratios. The P/Q weathering values obtained for the Paradox Basin samples are listed in Table 4-17. The data from the Spanish Valley and Gibson Dome localities are arranged as progressively older deposits or terraces. The weathering index, W (Table 4-17), eliminates the variation in soil parent material between sites by expressing the P/Q ratio for each soil horizon sample as a ratio to the P/Q value of the parent material at that location. Thus,

$$W = \frac{(P/Q)\ \text{sample}}{(P/Q)\ \text{parent material}}$$

Many of the soil profiles examined during this project developed in a composite of parent materials. An exposure may vary in complexity from a younger eolian unit overlying an older gravel deposit to up to four different depositional units containing two to three soils, as defined by field observation and soil laboratory analyses. The weathering indexes shown in Table 4-17 are normalized to the lowest sample analyzed for each soil profile. Because many were not described as being in an unoxidized C soil horizon in the field,

Table 4-17. Plagioclase/Quartz (P/Q) Weathering Ratios
(Page 1 of 3)

Locality	Formation[a]	Sample	Soil Horizon	P/Q	W	Remarks[b]
SPANISH VALLEY						
8	Modern	1-1		0.532		Fine-grained alluvial
		1-2		0.104		
16	Upper Member, Beaver Basin	5-6	2C1ca	0.319	1.16	
		5-5	2C30x	0.274	1.0	
18	Lower Member, Beaver Basin	4-3	B_2ca	0.365	0.43	Eolian
		4-4	2B3ca	0.658	1.03	
		4-10	3C2ca	0.641	1.0	
15	Upper Member, Placer Creek	3-1	A	0.431		Eolian
		3-2	B	0.341		Eolian
		3-7	2C1cab	0.315	0.80	
		3-9	2C2cab	0.634	1.62	
		3-11	2C3cacsb	0.453	1.15	
		3-6	2C3oxb	0.443	1.12	
		3-13	2C4oxb	0.395	1.0	
19	Lower Member, Placer Creek	7-7	2K2b	1.354	2.06	
		7-9	2C1cab	1.387	2.11	
		7-20	2C3csb	0.656	1.0	
17	Lower Member, Placer Creek	6-3	2K2mb	0.682	1.94	
		6-5	2C1cacsb	0.753	2.15	
		6-11,20	2C3csb	0.351	1.0	
20	Middle Member, Harpole Mesa	16-5	2K2mb	0.937	0.89	
		16-8	2C1cacsb	0.582	0.55	
		16-9	2C2cab	0.679	0.65	
		16-10	$3C_3$oxb	0.875	0.83	
		16-16	3C4oxb	0.860	0.82	
		16-18,21	3C4oxb	1.052	1.0	
21	Middle Member, Harpole Mesa	17-8	2K2b	0.880	2.12	
		17-10	2C1cacsb	0.989	2.38	
		17-12	3B1csb2	0.687	1.66	
		17-13	3B1csb2	0.738	1.78	
		17-14	3B2tcsb2	0.369	0.89	
		17-20,30	4B31cab2	0.329	0.79	
		17-23	4B31cab2	0.466	1.12	
		17-25	4B32b2	0.414	1.0	
		17-26	4Coxb2	0.415	1.0	

Table 4-17. Plagioclase/Quartz (P/Q) Weathering Ratios
(Page 2 of 3)

Locality	Formation[(a)]	Sample	Soil Horizon	P/Q	W	Remarks[(b)]
14	Lower Member, Harpole Mesa	18-1	A	0.345		Eolian
		18-2	Btca	0.229		Eolian
		18-4	C2Ca	0.255		Eolian
		18-10	2K22mb	0.644		
		18-12	2K31mb	0.585		Parent Material P/Q unknown
GIBSON DOME TERRACES						
32	8 (26)	14-3	B21T	0.265	0.34	Eolian
		14-8	2C1ca	0.292	0.37	
		14-10	2C2ca	0.787	1.0	
33	10 (32)	15-5	2C1ca	0.381	0.47	
		15-7	2C3ox	0.804	1.0	
34	10 (32)	13-3	2B2tca	0.331	1.40	Eolian
		13-6	3C2ca	0.237	1.0	
35	12 (40)	12-4	2C1ca	0.273	1.37	
		12-5,16	2C2ca	0.199	1.0	
		12-12	3C4ox	0.199	1.0	
36	12 (40)	11-1,10	Avca	0.380	1.21	Eolian
		11-3	B21tca	0.589	1.88	Eolian
		14-4	B22tca	0.516	1.65	Eolian
		11-5	2B23tca	0.249	0.80	Eolian
		11-7	2C1ca	0.243	0.78	Eolian
		11-9	3C3ox	0.313	1.0	
37	20 (66)	10-6,15	4C4ca	0.284	0.74	
		10-8	4C5ca	0.385	1.0	
38	20 (66)	9-2	B1	0.313	0.47	Eolian
		9-4	C1ca	0.326	0.49	Eolian
		9-7	2C4ca	0.314	0.48	
		9-9	2C6ca	0.660	1.0	
39	32 (105)	8-2	B1	0.339	0.76	Eolian
		8-3	B1	0.287	0.64	Eolian
		8-11	2C2ca	0.515	1.15	
		8-13	2C3ca	0.447	1.0	

Table 4-17. Plagioclase/Quartz (P/Q) Weathering Ratios
(Page 3 of 3)

Locality	Formation[a]	Sample	Soil Horizon	P/Q	W	Remarks[b]
URANIUM MILL SITE, WHITE MESA						
72		21-3	C1ca	0.351	1.04	Eolian
		21-5,15	C2ca	0.304	0.90	Eolian
		21-6	C3ca	0.257	0.76	Eolian
		21-8	2Btcab	0.344	1.02	Eolian
		21-10	2C1cab	0.202	0.60	Eolian
		21-11	2C2cab	0.338	1.0	Eolian

(a) Stratigraphic relationships are shown on Table 4-16. Localities shown on Figure 1-1, and listed in Table 1-1.

(b) X-ray analysis was made on silt-size material separated from gravel alluvium, unless otherwise stated.

these basal units are not always accurate representations of the parent material as defined by Isherwood (1975). However, the normalized values do demonstrate the trend (or lack thereof) of the data.

The trend observed by Isherwood (1975) of an increase in P/Q weathering ratios with depth is observed in data from only four of the 18 sites examined for the Paradox Basin study (Localities 32, 33, 37, and 38). However, only two samples from deposits at Localities 32 and 37 were analyzed (Table 4-17), so the trend assessment can be considered only tentative. Some other trends do appear in the P/Q ratios; low P/Q values (<0.5) are generally from eolian units, whereas some of the highest values are associated with the K soil horizons. Compared with the calcrete horizons, which may protect enclosed grains from the weathering process, the plagioclase in eolian silt appears more apt to be weathered, or to consist of weathered (recycled) plagioclase grains.

The inconsistency in the P/Q weathering data for soils in southeastern Utah may be due to several factors. The weathering process in the soil may be complicated by multiple parent materials having variable lithologies, and by the formation of calcic soils in these deposits. These complexities have probably been sufficient to disrupt indicators of weathering processes that are a function only of depth in a profile. Additionally, rainfall may not be sufficient for the minerals to weather in a manner comparable to that in areas where the method has been reported as showing definite trends with depth in the soil profile.

The samples submitted for this preliminary analysis represented only portions of the entire soil profile at each site; however, the data were sufficient to demonstrate the lack of the expected trend at these locations. Therefore, this particular application of X-ray diffraction data was not pursued further.

4.1.7.3.4.2 X-ray diffraction patterns. Quartz and feldspar data from six soil test pit sites in the Spanish Valley correlation area were examined as a preliminary evaluation of the use of X-ray diffraction patterns as a correlation and relative dating technique. Field and laboratory soil data had previously been collected and reported for these sites (WCC, 1982a, Vols. I and and V). At localities where data were sufficient to make comparative assessments, the trends or groupings of intensity values for the quartz and feldspar data correspond with the pedogenic or depositional zonations previously recognized for these sites. At Locality 21 (Figure 4-16), for example, at least three noticeable changes in intensity values and patterns of different X-ray peaks appear within the soil profile.

The soil profile for Locality 21 (Figure 4-17) had previously been described as indicative of a complex depositional history at that location, (WCC, 1982a, Vol. I, p. 3-14). On the basis of the soil laboratory data (Figure 4-17), a change in parent material was identified at a depth of 3.25 m (10.7 ft) within the anomalously clay-rich interval in the bottom half of the exposure. The X-ray data (Figure 4-16) strongly support a more shallow parent material boundary at 2.8 m (9.2 ft), where the clay content increases from 10 to 30 percent. The high-intensity values of the plagioclase and quartz minerals in this zone, and the continuity of these values with depth, are not characteristic of a pedogenic B horizon, however, and support the hypothesis that the clay-rich zone in this exposure may be depositional rather than pedogenic in origin.

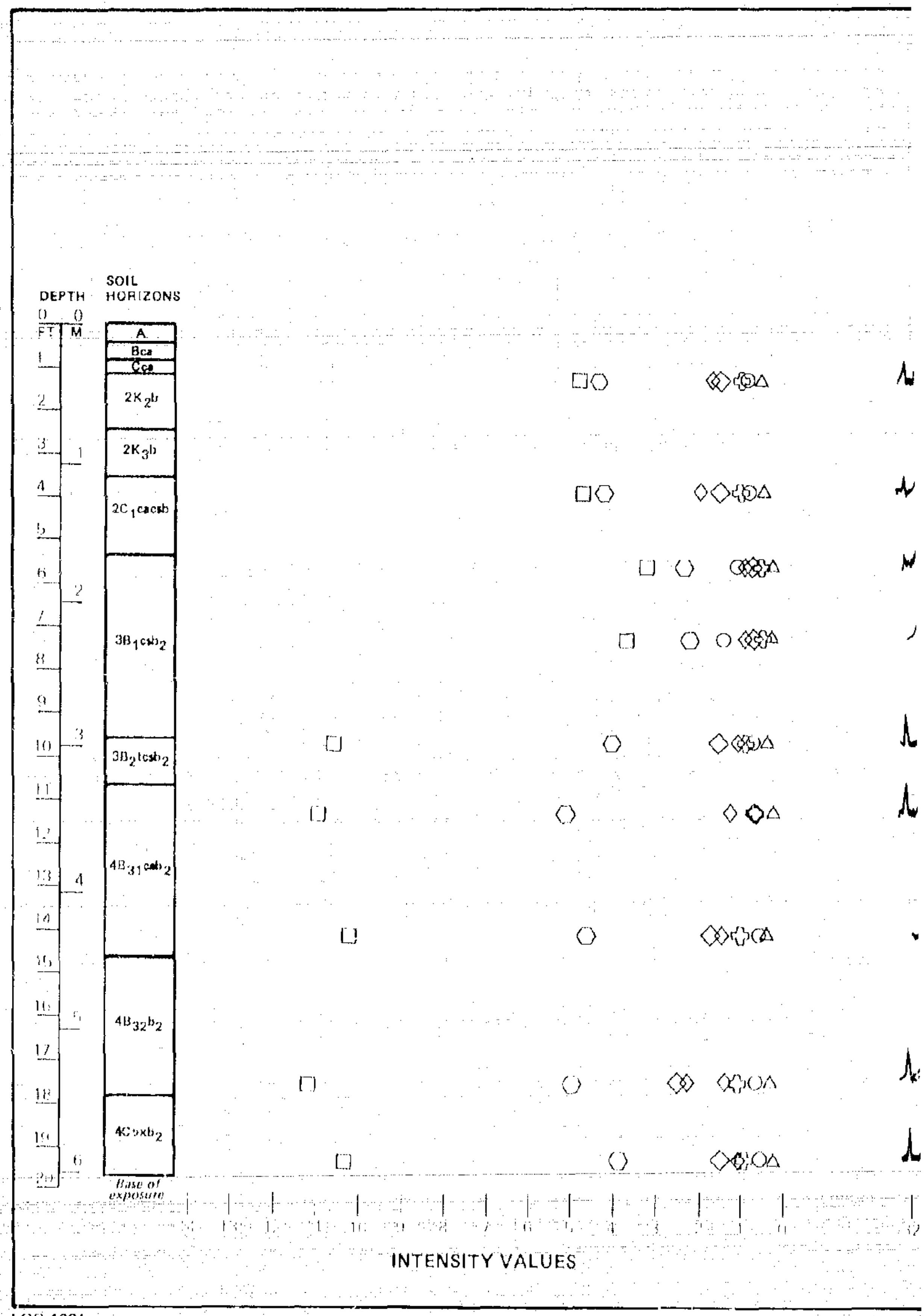
Most of the clay X-ray data did not show any consistent trends with depth or soil horizon, probably because most of the clays (probably >90 percent) had been removed in the laboratory, and the remaining amount did not provide a complete picture. The clay data at Locality 15 provide an indication of the type of data that could be obtained using this technique (Figure 4-18). The stacked intensity peaks vary with depth, mimicking the trends seen in the quartz and feldspar data.

In summary, the plagioclase and quartz data in X-ray diffractograms appear to be as useful as clay data in delineating weathering and depositional trends with depth. The specific nature of interpreted contacts can also commonly be identified by the characteristics of the X-ray trends. A depositional contact is likely to correspond with an abrupt change in curve characteristics, whereas a pedogenic boundary is more apt to be transitional. The quartz peak at 4.24Å and a plagioclase peak at 3.19Å exhibit the most variable intensity in a soil profile compared to other quartz and feldspar peaks, and therefore appear to be the most sensitive indicators of change with depth in this study. At the present time, comparison of actual intensity values of specific soil horizons (e.g., $2C_2ca$ or $2B_{22}t$) from deposits of increasing age does not provide a clear and definite trend with age. However, the overall tendency is for the intensity values of the quartz and plagioclase minerals to decrease with age.

A program that uses X-ray diffraction data to identify pedogenic horizons and to delineate depositional units and erosional events in Quaternary deposits should include X-ray analysis for quartz, feldspar, and clay minerals. To fully maximize the potential of this technique, samples should be collected from closely spaced point locations within each pedogenic or depositional unit of interest. A minimum recommended sample interval is 15 cm (6 in); at least three samples should be collected from each soil horizon. A complete X-ray analysis program should also include glycolated and heat-treated samples to distinguish clay minerals.

4.1.8 Topographic Position

The topographic positions of Quaternary terrace deposits and surfaces above present stream level provide a means of assessing their relative ages, particularly in an area such as the Colorado Plateau, where relief is high and stream incision has occurred for hundreds of thousands of years. A means of independently and accurately dating the terraces is commonly not available, so terrace height (topographic position) and long-term incision rates, used in conjunction with other dating techniques such as pedogenesis and TL dating, have been used to assess ages of deposits in the study areas. A quantitative age can be estimated for Quaternary materials if a long-term incision rate can be calculated for a particular drainage, or for a region as a whole. The most definitive rates are derived for areas where deposits that can be dated by some other means, such as radiometric dating of a volcanic ash, are incorporated in a river terrace deposit. An age estimate is derived by dividing the height of a deposit or surface above present stream level by the incision rate calculated for the area.


DEPTH
SOIL HORIZONS
FT
M
A
Bca
Cca
$2K_2b$
$2K_3b$
$2C_1cacsb$
$3B_1csb_2$
$3B_2tcsb_2$
$4B_{31}cab_2$
$4B_{32}b_2$
$4Coxb_2$
Base of exposure
INTENSITY VALUES

LOG 1601

PLOT OF INTENSITY OF NONCLAY MINERAL PEAKS AND X-RAY DIFFRACTOGRAMS VERSUS INTERPRETED SOIL HORIZONS AND DEPOSITIONAL BOUNDARIES

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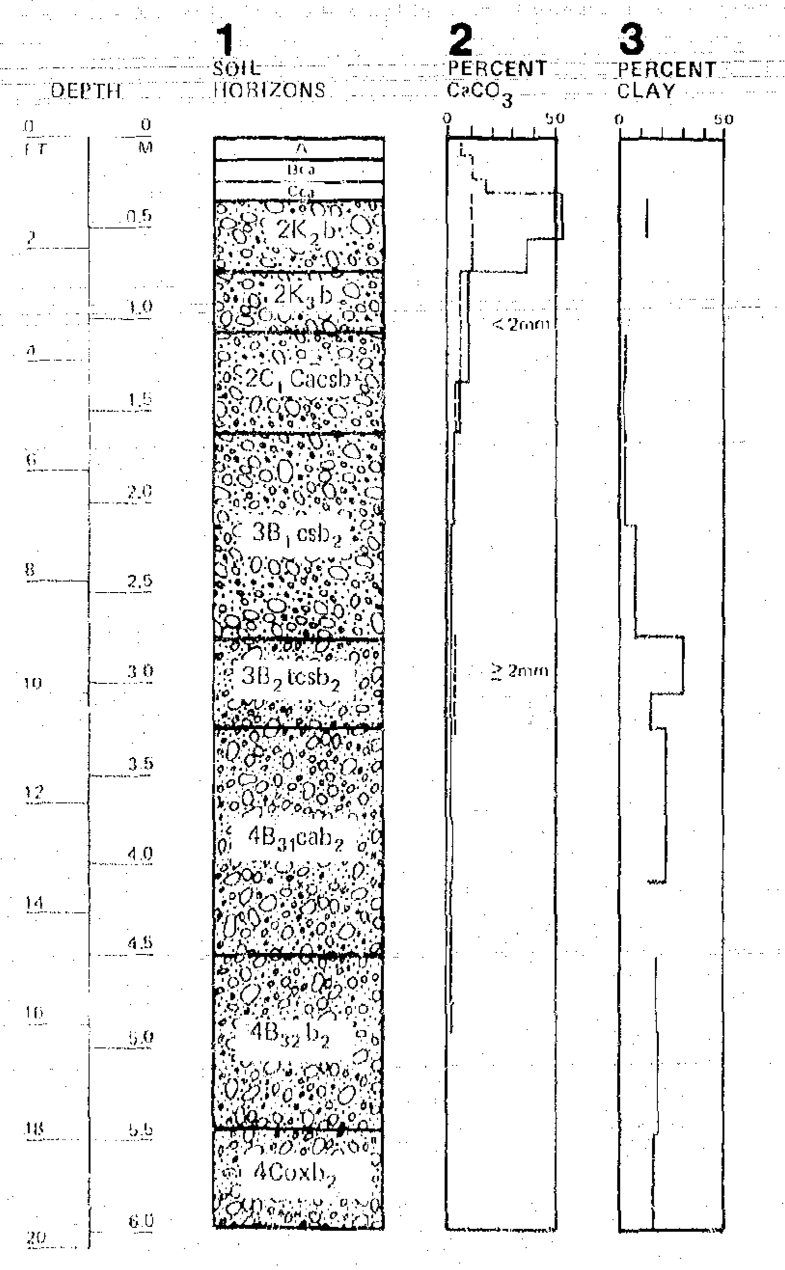
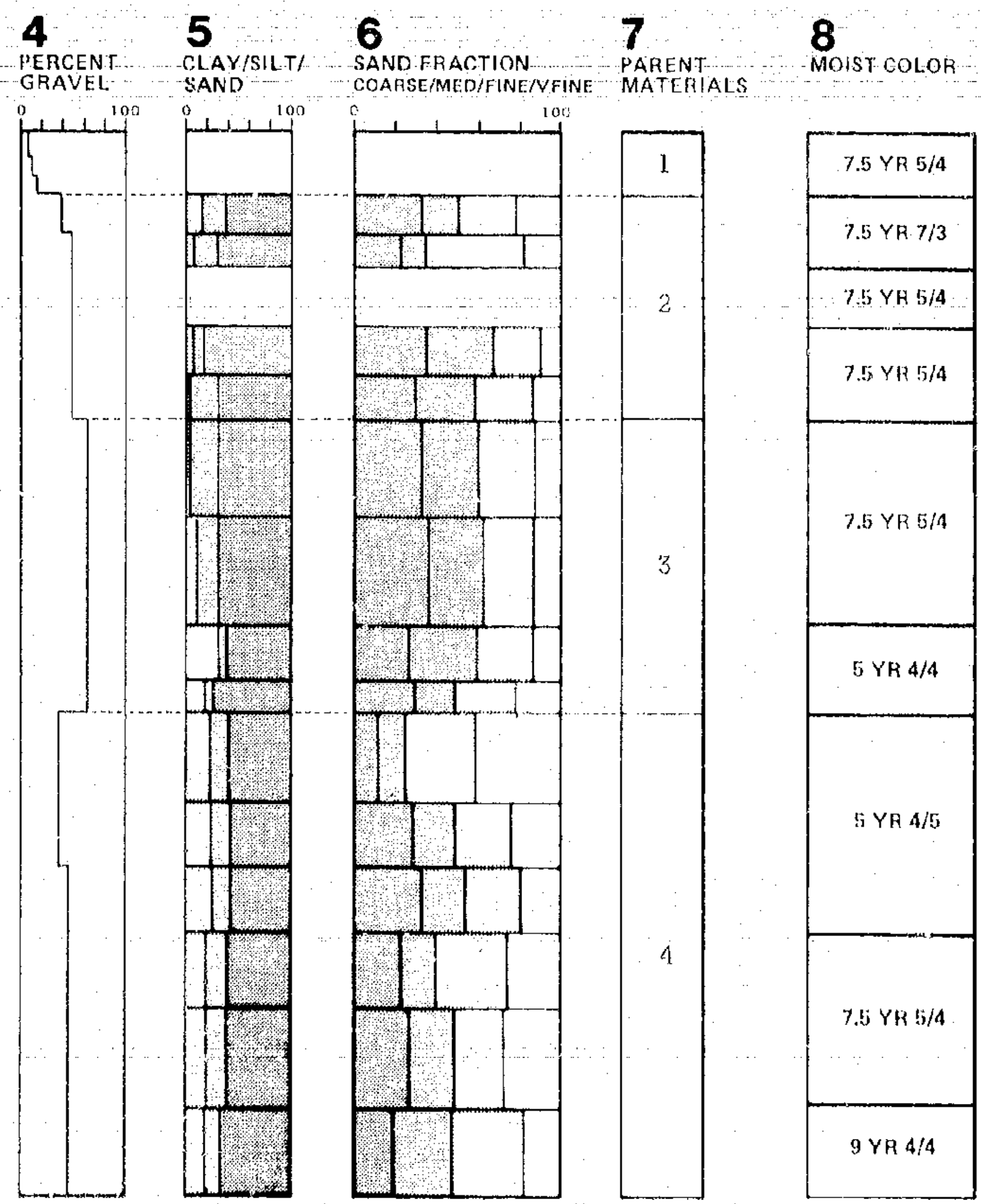
Figure 4-16



Source: Woodward–Clyde Consultants, 1982a



LOCALITY 21, SOIL PROFILE
MIDDLE HARPOLE MESA FORMATION

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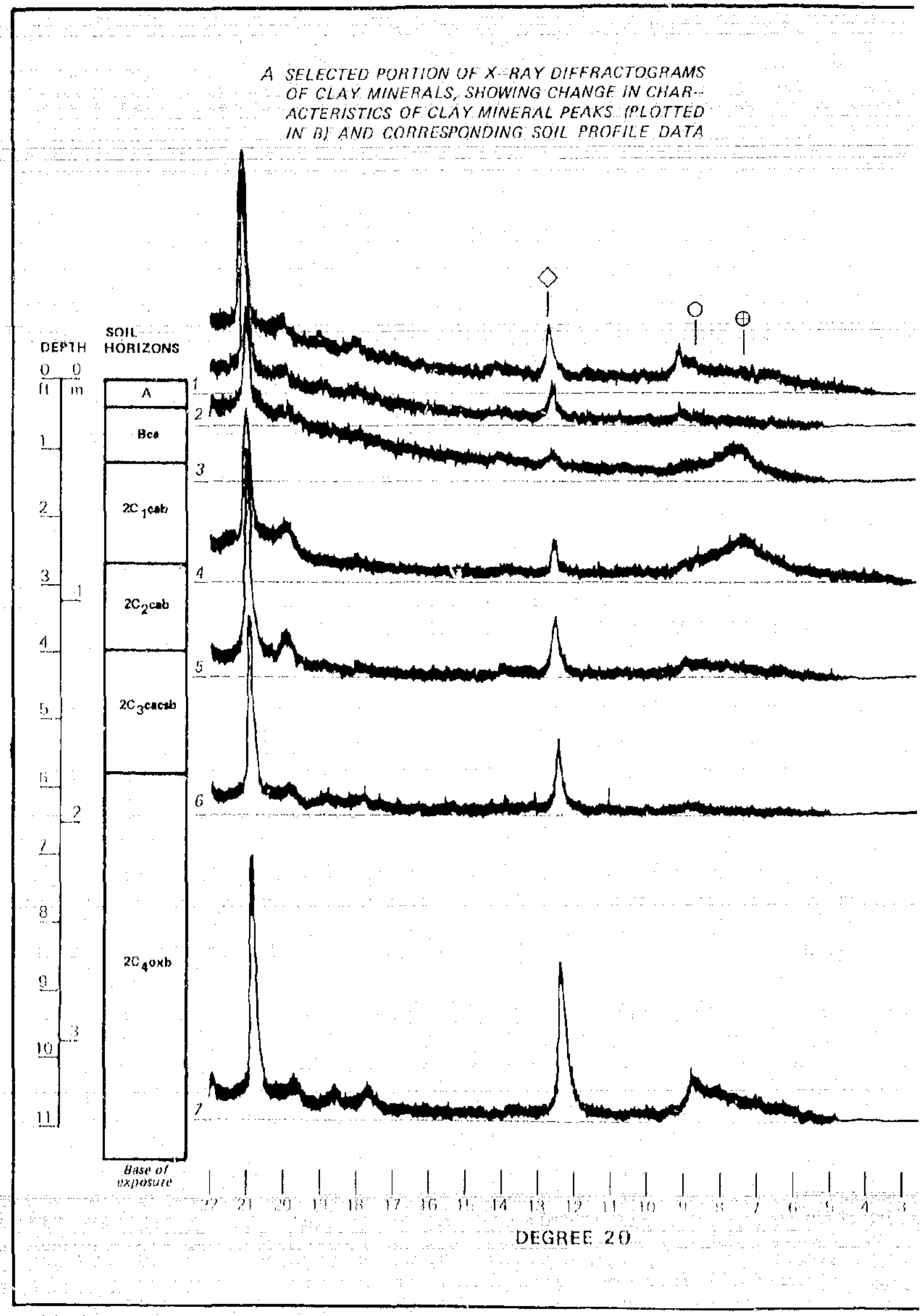
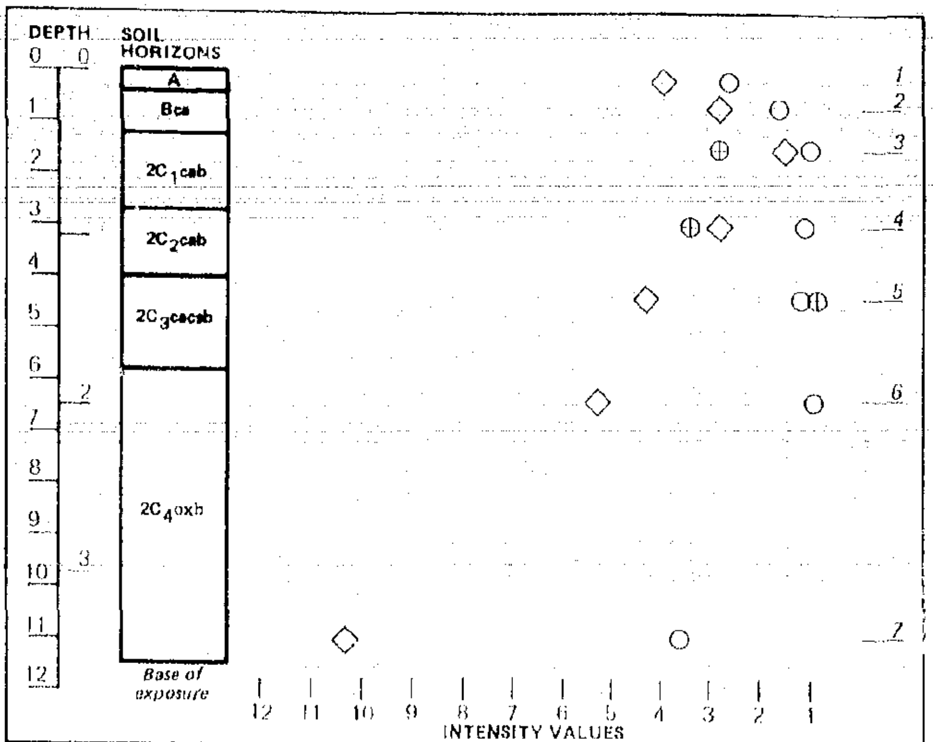
Figure 4-17



A SELECTED PORTION OF X-RAY DIFFRACTOGRAMS OF CLAY MINERALS, SHOWING CHANGE IN CHARACTERISTICS OF CLAY MINERAL PEAKS (PLOTTED IN B) AND CORRESPONDING SOIL PROFILE DATA
DEPTH
ft
m
SOIL HORIZONS
A
Bca
2C1cab
2C2cab
2C3cacsb
2C4oxb
Base of exposure
DEGREE 2θ



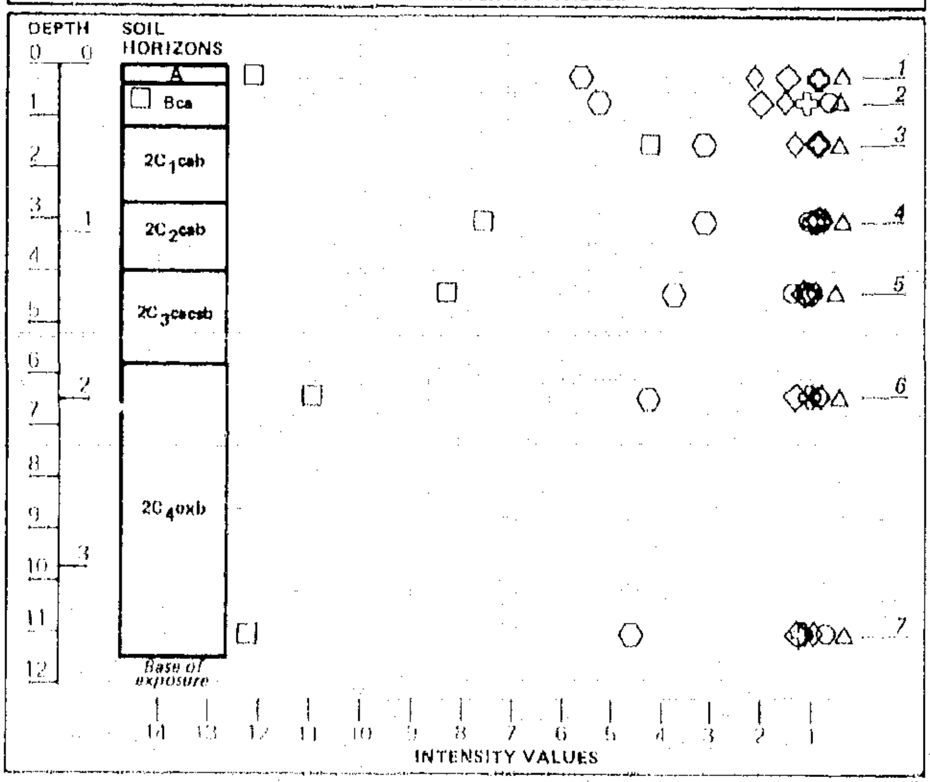
B RELATIVE INTENSITY VALUES OF CLAY MINERAL PEAKS, SHOWN WITH SOIL PROFILE DATA

LEGEND:

◇ KAOLINITE (7A)

○ ILLITE (10A)

⊕ SMECTITE (12.5A)



C RELATIVE INTENSITY VALUES OF NONCLAY MINERAL PEAKS, SHOWN WITH SOIL PROFILE DATA

LEGEND:

□ QUARTZ (4.24A)

○ PLAGIOCLASE (3.19A)

◇ ORTHOCLASE (3.79A)

◇ PLAGIOCLASE (4.03A)

✠ PLAGIOCLASE (3.67A)

○ ILLITE (4.49A)

△ ORTHOCLASE (3.87A)

LOCALITY 15

COMPARISON OF X-RAY INTENSITY OF SELECTED MINERALS WITH DEPTH AND WITH INTERPRETED SOILS AND DEPOSITIONAL BOUNDARIES
Quaternary Topical Report

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Woodward-Clyde Consultants

Figure 4-18

A long-term incision rate encompasses shorter term perturbations influenced by climatic changes and variable erodibility of successive bedrock strata. For example, many of the deposits available for study in the areas of interest to this project are fluvial terraces that probably formed in response to glacial and periglacial processes at higher elevations. During such periods, incision is apt to be episodic as streams adjust to variations in load and discharge.

A conservative long-term incision rate of 0.24 m (0.8 ft) per 1,000 years has been calculated for the major rivers (Colorado, San Juan, and Green Rivers) in the Paradox Basin region (WCC, 1983). This value is based on geomorphic positions of Quaternary deposits and their estimated ages, as reported in the literature for the Colorado River Basin in Utah, Colorado, northwestern New Mexico, and northern Arizona, and as derived from this study. Maximum incision rates, calculated by assuming minimum ages of deposits using reversed magnetic polarity and Stage IV to V pedogenic carbonate accumulation, are on the same order of magnitude as this rate (WCC, 1982a, Vol. 1, p 3-20).

In tectonically active areas, or areas that are subsiding as a result of salt flowage, dissolution, or some other cause, topographic position may not provide the accurate relative ages for a deposit. However, once an anomalous condition is recognized, relative elevations can provide insight into the amount of deformation, and perhaps into the rate at which deformation is occurring.

4.2 AGE DATING RESULTS OF SELECTED AREAS

Samples were collected for multiple age dating methods whenever a sufficient amount of appropriate materials was present at an individual locality. Collecting sufficient material was particularly important when the exposure was a backhoe soil pit that would be refilled after the description and sampling were finished. The age dating program was constantly evolving during the Paradox Basin study and some methods, such as TL dating, did not become available on a commercial basis until midway through the project. Therefore, although adequate and sufficient samples might have been available in soil profiles exposed by backhoe early in the project, either no suitable samples were collected for later analysis by the new dating technique, or some useful material was collected, but was not the optimum sample for that method. Measurement of pedogenic carbonate in the exposure is the only dating method that was universally applied at most of the soil profile localities. When TL analysis became available, stored samples from previously described localities were submitted in order to have some independent evaluation of the soil carbonate ages.

Results of the dating program can be compared for areas where data from multiple techniques are available. These areas include the Spanish Valley correlation area and vicinity, including Green River terraces; the Gibson Dome area and vicinity; and the Elk Ridge area and vicinity, including the Blanding area and Colorado River terraces. Initial detailed sampling and analysis of the chronostratographic units in Spanish Valley were completed to develop a means of assessing the age of Quaternary deposits elsewhere in the Paradox Basin. Comparable evaluations were later made on soil profiles developed in

Quaternary deposits in the Gibson Dome and Elk Ridge study areas. Deposits west of the Green River were examined to enhance the data base for long-term carbonate influx rates.

4.2.1 Spanish Valley and Vicinity

Soils and Quaternary deposits were examined and sampled for a series of fluvial terrace deposits in Spanish Valley (primarily exposed in backhoe trenches excavated for this study); in natural exposures of terrace and other fluvial deposits west of the Green River Canyon; and in deposits exposed in Bartlett Wash, northwest of Moab.

4.2.1.1 Spanish Valley

Classical correlations of deposits require a type section of similar stratigraphy that has been chronologically and lithologically defined by previous workers. In the late 1950s, Richmond (1962) established a Quaternary stratigraphy for the La Sal Mountains and vicinity; his chronology provided the needed correlation for the Paradox Basin study (Table 4-16). The Spanish Valley area on the northwest side of the La Sal Mountains (southeast of Moab) was selected as a correlation area for this project because it contains a good sequence of fluvial terrace deposits of late and middle Pleistocene age, and because it is similar to the Gibson Dome and Elk Ridge study areas with respect to climate, elevation, and deposits. The terrace deposits, for example, have similar parent lithologies and textures in all three areas. The rate of soil formation in the Spanish Valley area should therefore be comparable to that in the other study areas.

The bulk of the age dating studies done in Spanish Valley were focused on fluvial terrace deposits along Pack Creek, southeast of Moab (WCC, 1982a, Vol. I) (Figure 4-19). Additional data were also collected for two other Spanish Valley locations: a gravel pit near Moab (Locality 6), and a permeability pit for a gravel operation in the center of the valley (Locality 13). These two sites were not studied in the detail given the terrace deposits, but they were used to further compare and evaluate age dating methods.

4.2.1.1.1 Spanish Valley Correlation Terraces, Localities 14, and 16 to 21. Almost all of the dating techniques described in Section 4.1 were applied to the deposits in the Spanish Valley correlation area. Topographic position, pedogenic properties, and TL dating provided the most consistent means of age assessment of these deposits and are described in this section. In addition, depositional and pedogenic boundaries, interpreted from X-ray diffractograms, correlate with Spanish Valley soil profiles developed from field and particle size data. Dating methods based on amino acid analyses of soils, weathering rind measurements, and weathering of heavy mineral grains were judged to be inconclusive for the area. No material suitable for radiocarbon analysis or amino acid analysis of snail shells was found in the correlation terraces in Spanish Valley.

Age estimates based on calcic soil development in the Spanish Valley correlation terraces were reported in WCC, 1982a (Vol. I), and are compared with derived TL dates in Table 4-18. Age estimates based on the height of the terraces above present stream level (topographic position) are given in Table 1-1. In a comparison of the three data sets, some correlations are evident. The amount of pedogenic carbonate accumulated in a profile and the derived TL dates generally increase as the height of the deposit above present stream level increases. However, this relationship is complicated in the middle of Spanish Valley by tectonics, or salt flowage, or dissolution and subsidence; and older deposits are buried by younger material (WCC, 1982a, Vol I). Although the terrace deposits commonly consist of fine-grained (possibly eolian) deposits over coarse gravel, the interpretation reached in pedologic studies is that only one soil has developed in the composite deposits on terraces that are late Placer Creek or younger in age.

Deposits of gravel and eolian material that underlie two terrace remnants (Localities 16 and 18; Figure 4-19) of Beaver Basin age (approximately 130,000 to 10,000 years BP) have TL ages of 11,900±760 years BP for the fine-grained deposits, and 9,290±700 and 42,400±2,770 years BP for the gravel deposits. Calcic soil derived dates range from 30,000 to 60,000 years. These dates are consistent with Richmond's (1962) age assignment of late Pleistocene to the Beaver Basin Formation, and with the inferred correlation with Pinedale deposits in the Rocky Mountain region (Colman and Pierce, 1977; Table 4-16). However, the two younger TL dates are near the Holocene/late Pleistocene boundary, and are thought to be too young for the deposit. These dates may reflect the contamination by younger eolian fine-grained particles that have filtered downward into the sample horizon.

Deposits of the Placer Creek Formation (approximately 200,000 to 130,000 years in age) are readily separable from the Beaver Basin deposits on the basis of better calcic soil development (WCC, 1982a, Vol. I). The Placer Creek deposits yielded significantly older TL dates, which ranged from 108,000±8,400 to 238,310±18,5200 years BP in age, from three terrace remnants in Spanish Valley (Localities 15, 17, and 19; Table 4-18). Calcic soil dates derived from the same exposure ranged from 145,000 to 255,000. These dates are in agreement with recent ages assigned to correlative Bull Lake deposits in the Rocky Mountain region (Colman and Pierce, 1981; Shroba, 1982, Shroba et al., 1983). When the calcic soil and TL dates are compared by sample locality (Table 4-18), the TL dates are younger than the calcic soil dates at two of the three sampled locations.

Deposits of the middle member of the Harpole Mesa Formation, considered mid-Pleistocene (approximately 730,000 to 300,000 years) in age (Richmond, 1962; Table 4-16), were sampled from two backhoe pits (Localities 20 and 21, Figure 4-19). The derived TL dates are more variable than those for the younger deposits, and some dates are significantly younger than the inferred age for this formation (Tables 4-16 and 4-18). Three of the six dates are indicative of the expected age of the deposit (>200,000, >315,000, 319,000±37,000 years); however, reproducibility of these data is poor (Tables 4-10 and 4-18). The results of two duplicate data sets from Localities 20 and 21 consist of a young date (67,600±5,300 years and 124,210±10,370 years) and a much older date (>315,000 and 319,000 years). Both sets of samples were collected within 0.2 m (0.5 ft) of the base of the overlying eolian deposits, and perhaps were nonhomogeneously contaminated by

Table 4-18 Comparison of Calcic Soil Ages and Thermoluminescence Dates, Spanish Valley Area (Page 1 of 2)

Geologic Epoch (10^3 years)	Formation	Locality[a]	Site	$CaCO_3$ age[b] (10^3 years)	TL date (10^3 BP)	TL Lab No. (ALPHA-)	Comments on TL Samples
Holocene (0 to ca 10)	Gold Basin	7	Sec. 22, T26S, R22E-1	8 - 13	"too young to date"	467	1.3 m (4 ft) depth.
					7.48 ± 0.61	466	2.0 m (6.5 ft) depth.
Late Pleistocene (ca 10 to 130)	Upper Member, Beaver Basin	16	Sec. 17, T27S, R23E-1	35 - 60	42.4 ± 2.77	434	Collected in gravel, 0.3 - 0.4 m (1 - 1.5 ft) below eolian cover.
	Lower Member, Beaver Basin	18	Sec. 18, T27S, R23E-2	30 - 45	11.9 ± 0.76	436	Collected in eolian deposits, 0.4 m (1.5 ft) depth.
					9.29 ± 0.7	535	Collected in gravel, 0.2 m (0.7 ft) below eolian cover.
Middle-Pleistocene (ca 130 to 730)	Upper Member, Placer Creek	15	Sec. 16, T27S, R23E-1	150 - 245	238.31 ± 18.52	534	Collected in gravel, 0.1 - 0.2 m (0.5 ft) below eolian cover.
	Lower Member, Placer Creek	17	Sec. 16, T27S, R23E-1	145 - 240	108.0 ± 8.4	435	Collected in gravel, 0.2 m (0.7 ft) below eolian cover.
	Lower Member, Placer Creek	19	Sec. 20, T27S, R23E-1	150 - 255	111.0 ± 13.0 127.0 ± 16.4	439 438	Duplicate samples; collected in gravel, 0.3 m (1 ft) below eolian cover.
	Middle Member, Harpole Mesa	20	Sec. 22 T27S, R23E-1	115 - 195	22.5 ± 2.0	440	Collected in eolian deposits, 0.1 - 0.2 m (0.5 ft) depth.
					67.6 ± 5.3 >315	437 536	Duplicate TL samples; collected in gravel 0.2 m (0.5 ft) below eolian cover.
					102.75 ± 13.4	548	Collected in gravel at depth of 2.1 m (7 ft).

Table 4-18. Comparison of Calcic Soil Ages and Thermoluminescence Dates, Spanish Valley Area (Page 2 of 2)

Geologic Epoch (10^3 years)	Formation	Locality[a]	Site	$CaCO_3$ age[b] (10^3 years)	TL date (10^3 BP	TL Lab No. (ALPHA-)	Comments on TL Samples
	Middle Member, Harpole Mesa	21	Sec. 28, T27S, R23E-1	165 - 275	124.21 ± 10.37 319 ± 37	538 441	Duplicate samples collected in gravel, 0.2 m (0.5 ft) below eolian cover.
					>200	539	Collected in gravel at depth of 2.1 m (7 ft).
Early Pleistocene (ca 730 - 1,800)	Lower Member Harpole Mesa	9	Sec. 32, T26S, R23E-1	730[c]	263.17 ± 45.22	547	Collected from sand lens in gravel deposit.
		14	Sec. 5, T27S, R23E-2	730[c]	167.78 ± 12.43	553	Collected in gravel 0.5 m (1.8 ft) below eolian cover.

(a) Refer to Table 1-1 and Figure 1-1.
(b) Age based on a carbonate accumulation rate of 0.15 - 0.25 g/cm^2/1,000 years.
(c) Age based on paleomagnetically reversed sediments.

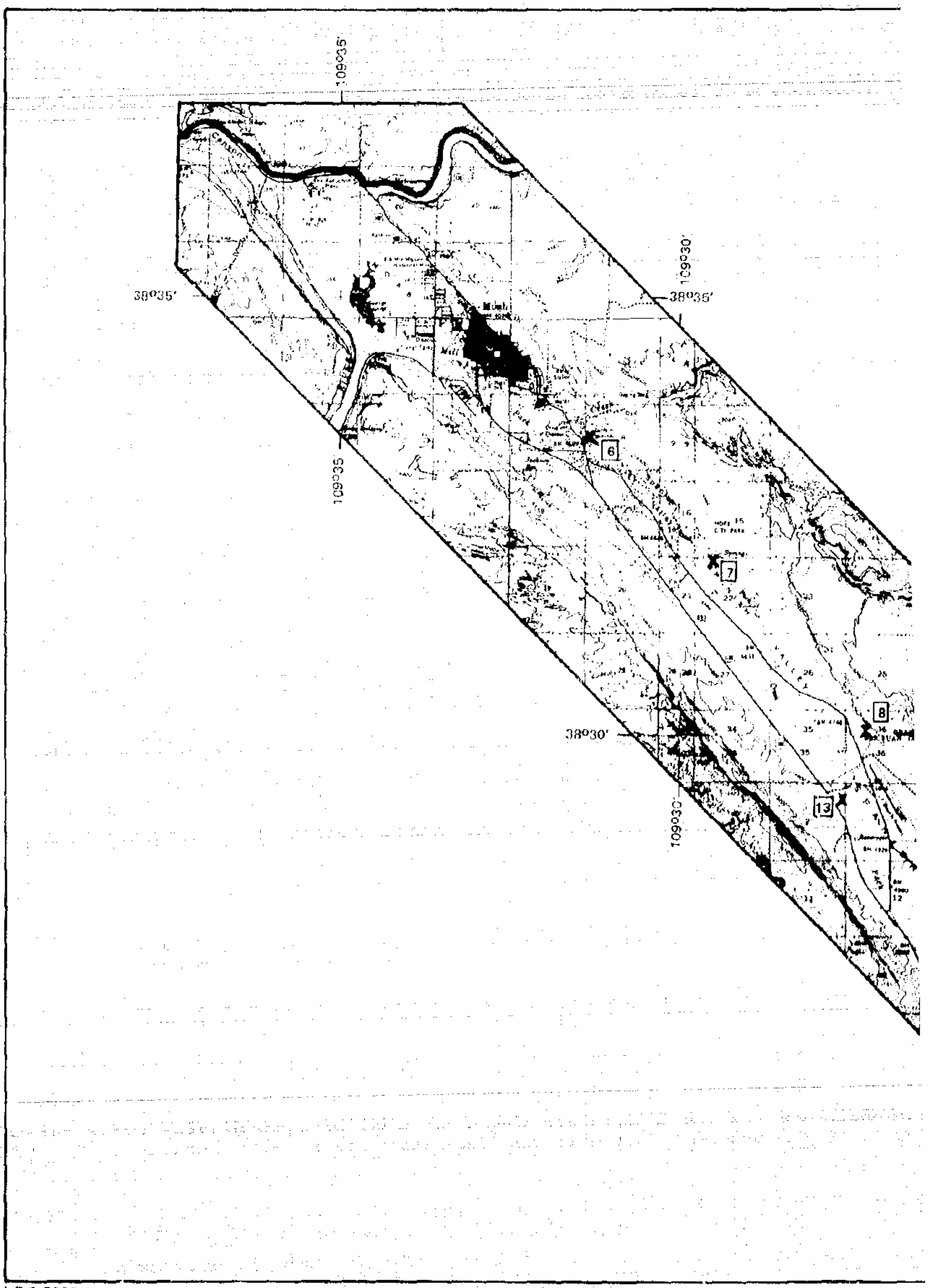
fines that moved downward through the gravel from the younger overburden. The younger dates are judged to be erroneous for the deposits; the older dates more accurately reflect the age inferred for the deposit.

Age estimates based on calcic soil development at Localities 20 and 21 are comparable to the younger TL dates. Calcic soils in the deposits of the middle member of Harpole Mesa are similar to those developed in the lower member of the Placer Creek alluvium, and the carbonate accumulation ages of 115,000 to 275,000 years (Table 4-18) are much younger than the expected age of the deposits. A buried clay-rich stratum approximately 2 m (6 ft) thick at Locality 21 was originally thought to be a buried soil; this interpretation is supported by the amino acid data (Section 4.1.4.3.2). However, the uniformly high clay content throughout the profile (WCC, 1982a, Vol. I, p. 3-13) and the recently examined X-ray diffraction data for the soil-test pit (Section 4.1.7.3.4.2) suggest that the high clay content probably reflects the original character of the deposit, rather than lengthy pedogenic processes. Additional studies are required to assign a more definitive age to the deposits.

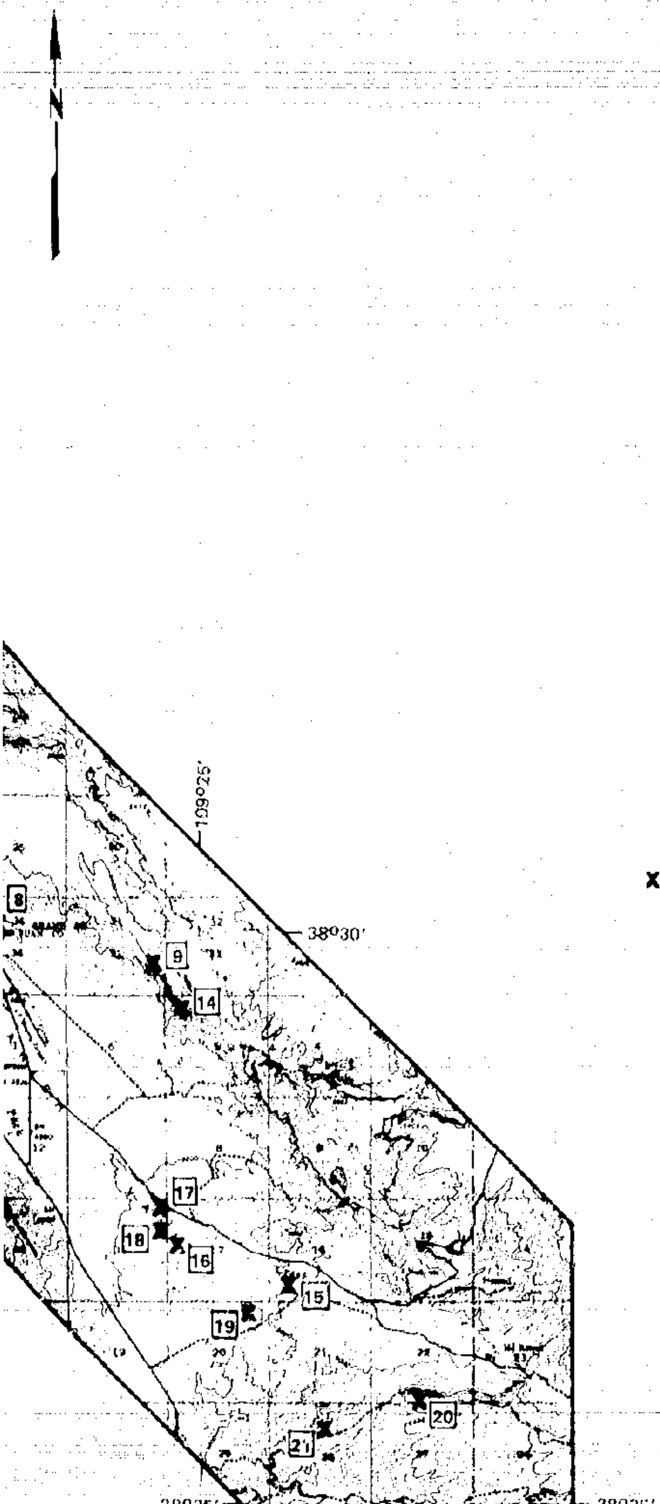
The highest terrace deposit (260 m [850 ft]) sampled in Spanish Valley is on Johnson's-Up-On-Top (Localities 9 and 14). This surface is estimated to be at least 1,000,000 years old on the basis of long-term incision rates and the elevation of the surface above present stream level. An age on that order of magnitude (>730,000 years) is substantiated by reversed magnetic polarity of the deposit and the high (182 g/cm^2) pedogenic carbonate content in its soil column. The assumed age of 730,000 years for these deposits and the measured soil carbonate data provide the upper bound of 0.25 g/cm^2/1,000 years for the carbonate influx rate used in the Paradox Basin soil studies.

The TL samples collected from the cemented K soil horizon on Johnson's-Up-On-Top and from a sand lens in the gravel beneath the soil provide dates of 167,780$\pm$12,430 and 263,170$\pm$45,220 years BP, respectively. Both these TL dates and those for Green River and Colorado River terraces (Sections 4.2.1.2 and 4.2.3.3) of probable comparable age are consistently young compared to the expected ages of the deposits. These data suggest that (1) the deposits are older than the applicable time span for the TL dating techniques, (2) the deposits have reached saturation with regard to TL content, (3) younger fine-grained material of eolian origin has been incorporated into the soil profile as it was forming, or (4) some other factor is affecting the TL signal in the formation of the petrocalcic soil.

4.2.1.1.2 <u>Moab Gravel Pit, Locality 6</u>. The Moab gravel pit (Locality 6, Figure 4-19) is excavated in a terrace remnant that is 12 m (40 ft) above present stream level on the eastern side of Moab. Richmond (1962, Plate J) identified these deposits as Placer Creek Formation (Table 4-16), an interpretation supported by the extent of clay and carbonate accumulation observed in the soil profile (WCC, 1982a, Vol. I). During the present study, a probable U-series date of 15,000$\pm$1,000 years (maximum age 72,000$\pm$6,000 years) was obtained on carbonate rinds cemented to gravel clasts in the most developed calcic soil horizon (Section 4.1.6.3). A terrace age of approximately 50,000 years is estimated from the height of the deposits above



LOG 2332



EXPLANATION

X [19] SAMPLE LOCALITY

LOCATION OF SAMPLE LOCALITIES
SPANISH VALLEY

Quaternary Topical Report

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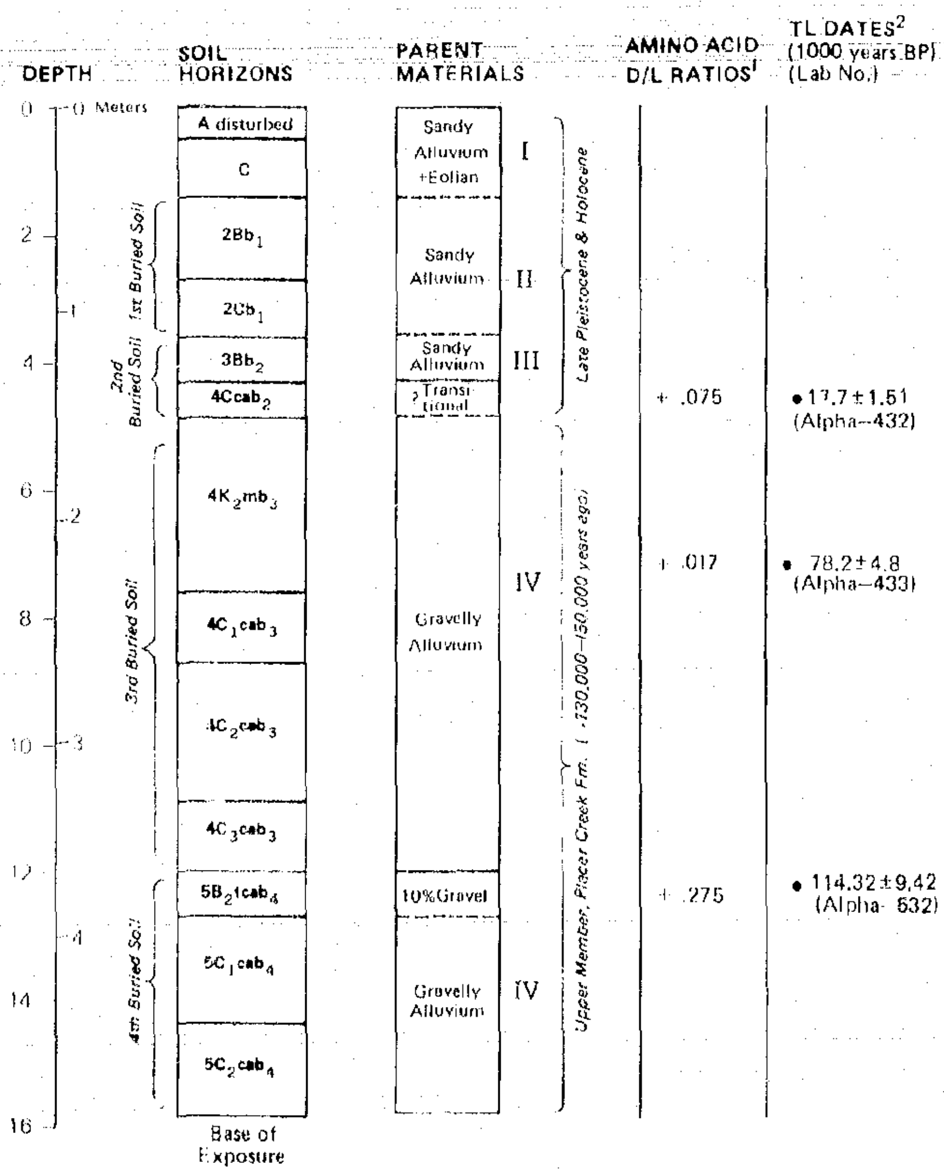
the present stream level, using the long-term incision rate of 0.24 m (0.8 ft) per 1,000 years. Both of these age estimates fall within the time range of Beaver Basin deposits (Table 4-16).

The amount of pedogenic carbonate accumulated in the soil profile, approximately 61 gm/cm^2, indicates a much older age for the deposit. Using carbonate influx rates of 0.15 to 0.25 gm/cm^2/1,000 years, an age range of 245,000 to 405,000 years was obtained. These dates appear to be old in view of the low elevation of the terrace, and fall within the proposed time span of the upper and middle members of the Harpole Mesa Formation (Table 4-16). An alternate explanation for the apparently anomalously high pedogenic carbonate content of the deposit is not readily available. An early Beaver Basin age, such as the maximum range of the U-series data, or a late Placer Creek age (Richmond's original interpretation) are still considered the most valid ages for this deposit, primarily because of its topographic position in Spanish Valley.

4.2.1.1.3 Permeability Pit, Locality 13. Bulldozer trenches have been excavated in gravel mapped as Beaver Basin Formation (Richmond, 1962; WCC, 1982a, Vol. I, Figure 3-15) near gravel pit operations in Spanish Valley at Locality 13, southeast of Moab (Figure 4-19). To learn more of the depositional history in Spanish Valley (WCC, 1982a, Vol. I, p. 3-15), soil development was examined in these exposures, which reached depths of 4.5 to 6 m (15 to 20 ft). The soil profile was described, but not systematically sampled; material was collected for amino-acid-analysis dating of soils, and for TL dating. The location is referred to as the "permeability pit."

Four buried soils were interpreted in this exposure. The upper two soils are in sandy alluvium, and the lower two are in gravelly alluvium (Figure 4-20). The second buried soil is interpreted as late Pleistocene (Beaver Basin) in age, on the basis of pedogenic development. A TL date of 17,700$\pm$1,510 years BP derived for this deposit is assessed to be too young. The two lower buried soils are tentatively correlated with the soils developed on the Placer Creek Formation on the basis of their visible carbonate content, which was described as a K soil horizon in the field and is assumed to be pedogenic in origin. The TL dates of 78,200$\pm$4,800 and 114,320$\pm$9,420 are stratigraphically consistent, but are slightly younger than others reported for this formation elsewhere in Spanish Valley (Table 4-18). They are also younger than the hypothesized age (130,000 to 200,000 years of the Placer Creek Formation (Table 4-16). On the basis of the well-developed character of the calcic soil, these TL dates are also judged to be too young. Alternatively, it is possible that the K horizon is partially ground-water deposited, and hence appears to be older than it actually is; in this case, the TL dates could be accurate.

The TL dates support the interpretation (originally based on soil development) that alluvial deposits are progressively older with depth in the central portion of Spanish Valley, and that Beaver Basin deposits overlie Placer Creek deposits in that area. Both upstream and downstream of the permeability pit, deposits mapped as Placer Creek Formation are topographically higher than the Beaver Basin deposits. The inverse relationship observed in the central part of the valley has been interpreted as due to



LEGEND:

Location shown on Figures 1-1 and 4-19

1 Discussed in Sections 4.1.4 and 4.2.1.1.3 of text

2 Discussed in Sections 4.1.3 and 4.2.1.1.3 of text

$3Bb_2$ Classification of Soil Horizon

II Stage of Soil Carbonate Morphology

PERMEABILITY PIT, SPANISH VALLEY, LOCALITY 13; SOIL PROFILE, AMINO ACID RATIOS, AND THERMOLUMINESCENCE DATES

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Figure 4–20

downwarping, or differential subsidence of the valley floor since Placer Creek time. This deformation could be caused by tectonism, or by dissolution or migration of salt at depth.

4.2.1.2 Green River Terraces, Localities 3, 4, 5, and 12

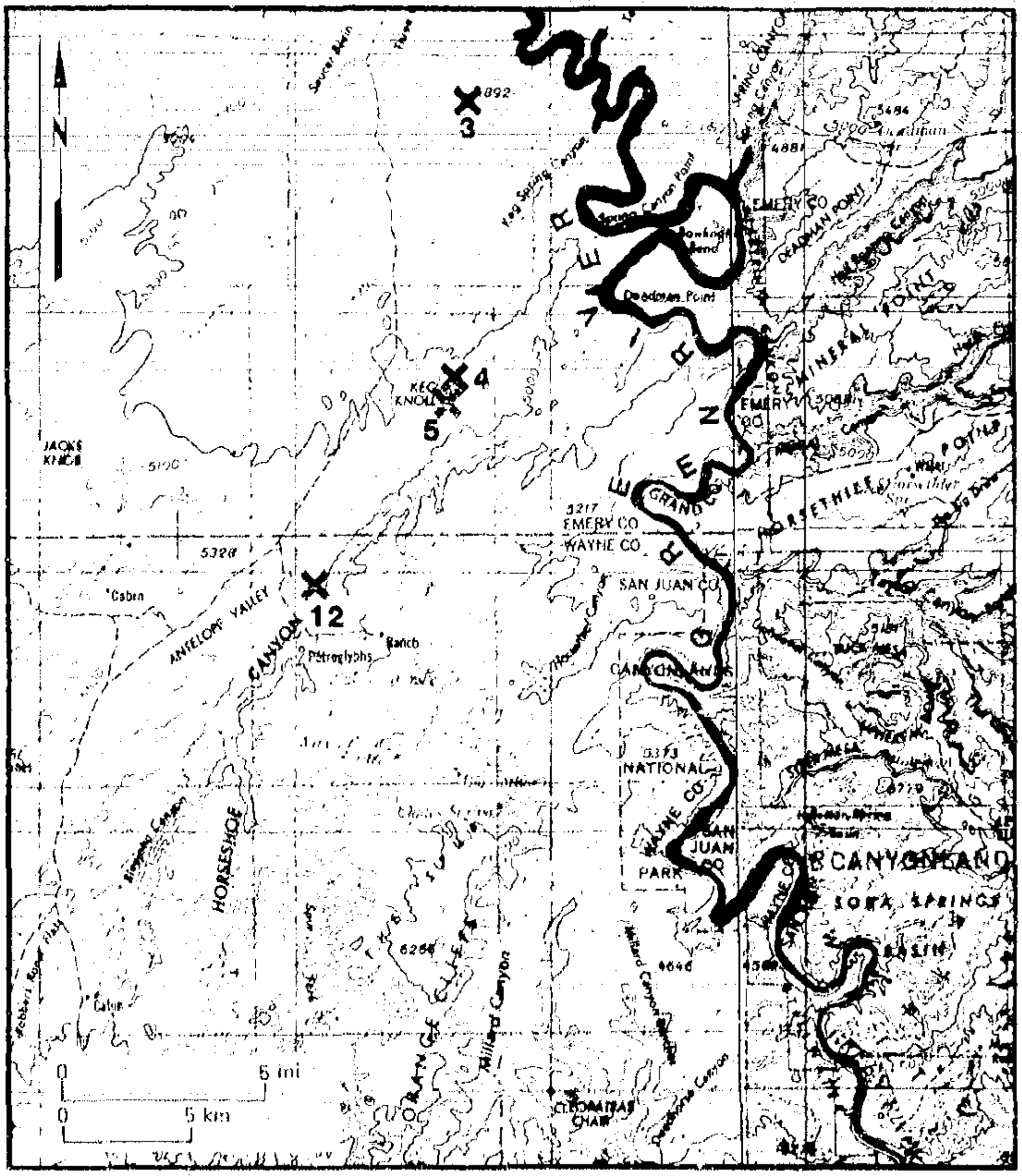
West of Moab and the Green River, remnants of fluvial gravel deposits occur on an erosion surface 240 to 400 m (800 to 1,300 ft) above the present canyon bottom. The gravel contains clasts indicating deposition by the ancestral Green River. The remnants are protected by a petrocalcic cap that has Stage V carbonate morphology and has developed either in the gravels or in fine-grained (eolian?) material above the gravel. These deposits, and others like them on strath terraces high above the Colorado River west of the Elk Ridge Area (Section 4.2.3.3), are of interest to the Paradox Basin studies because they can be used to calculate long-term incision rates for the major rivers in this part of the Colorado Plateau.

Samples were collected from the Green River terraces to measure the magnetic polarity and carbonate content of the deposits, and to derive a date for the deposits by TL analysis. Reversed(?) paleomagnetic polarity was measured at Locality 5 (Figure 4-21), and measurements of questionable polarity were made at Antelope Valley (Locality 12). However, on the basis of the demagnetization data, calcic soil development (Figure 4-22) and topographic position, the Antelope Valley gravels were also judged to be at least 730,000 years old (WCC, 1982a, Vol. I, p. 3-18). The pedogenic carbonate accumulated in the soil profile (between 93 and 128 g/cm^2) at Antelope Valley provides the long-term maximum carbonate accumulation rate of 0.15 g/cm^2/1,000 years. This rate has been applied to other soil carbonate studies conducted for the project.

One TL date was derived from the Green River terraces (Table 4-19). The date of 134,000$\pm$19,300 years BP derived for a K soil horizon at Locality 4 is much younger than the expected age of the deposits, and is therefore believed to be erroneous. The particle size of two other samples submitted for TL dating was judged by the laboratory to be unsuitable for analysis because it was too inhomogeneous.

4.2.1.3 Bartlett Wash, Localities 1 and 2

Previously unmapped alluvial fill rests unconformably on the Summerville and Entrada Formations in Bartlett Wash and in the adjacent wash to the north (Localities 2 and 1, respectively; Figure 4-23 and Table 1-1). This deposit is directly west of the Moab fault, northwest of Moab. The alluvium consists of at least 15 m (50 ft) of well-consolidated, alternating sandy and clayey material. Layers of finely bedded $CaCO_3$ of uncertain origin are present near the top of the section. The discovery of a mammoth tusk in this area suggests that the deposits may be pre-Holocene in age; radiocarbon age determinations made on the tusk range from dates of 12,880$\pm$370 years to >35,000 years BP (Tables 1-1 and 4-6); a U-series date of approximately 45,000 BP (Table 4-15) was obtained. Amino acid racemization data from snails in a sandy unit approximately 3 m (10 ft) above the tusk give an estimated age of 11,000 to 15,000 years (Table 4-12); these dates support the younger radiocarbon date



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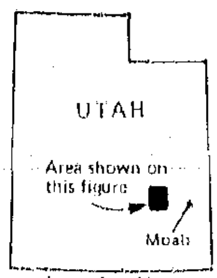
X 12 LOCALITY NUMBER, AS LISTED ON TABLE 1–1



Location Map

LOCATION OF SAMPLE LOCALITIES WEST OF THE GREEN RIVER Quaternary Topical Report	
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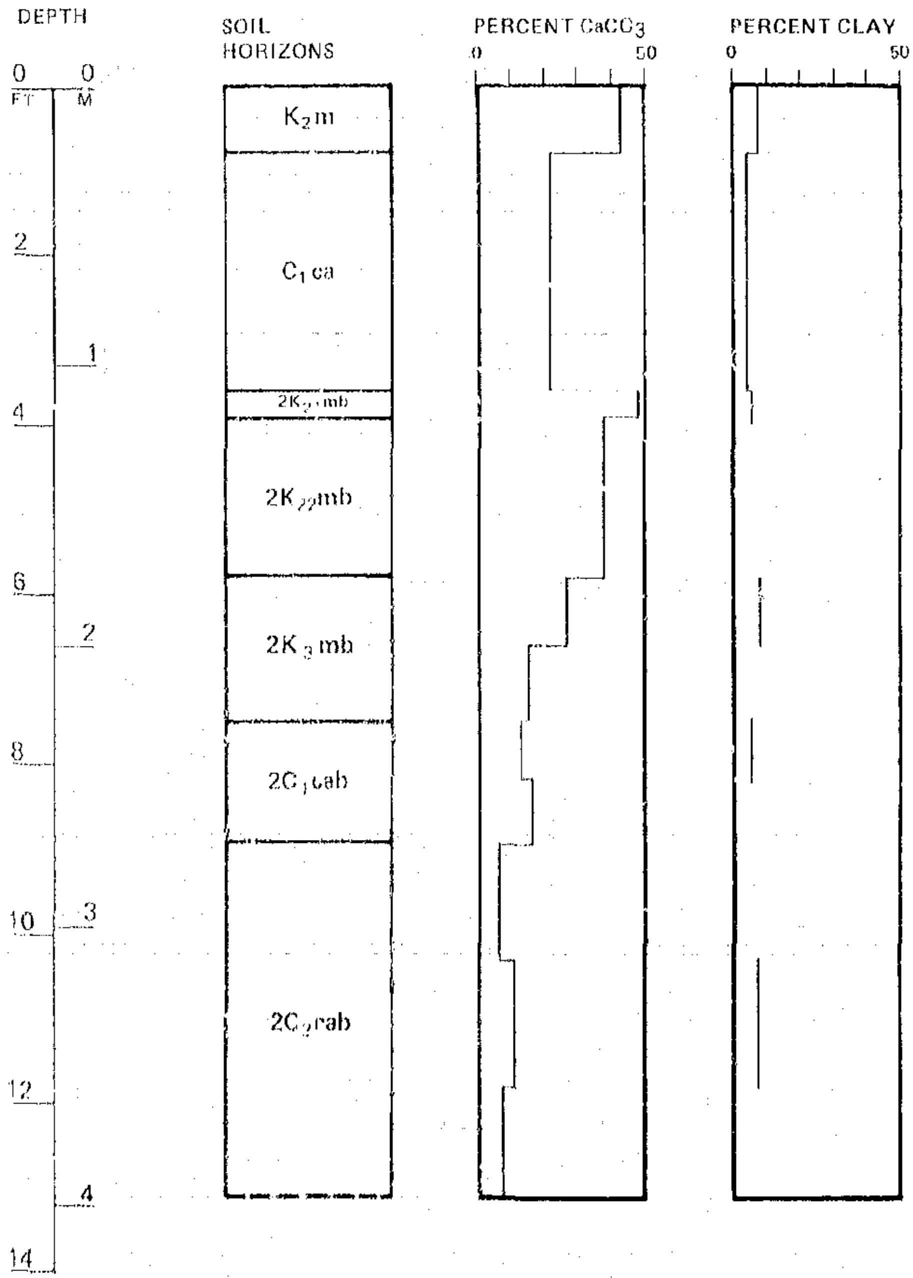
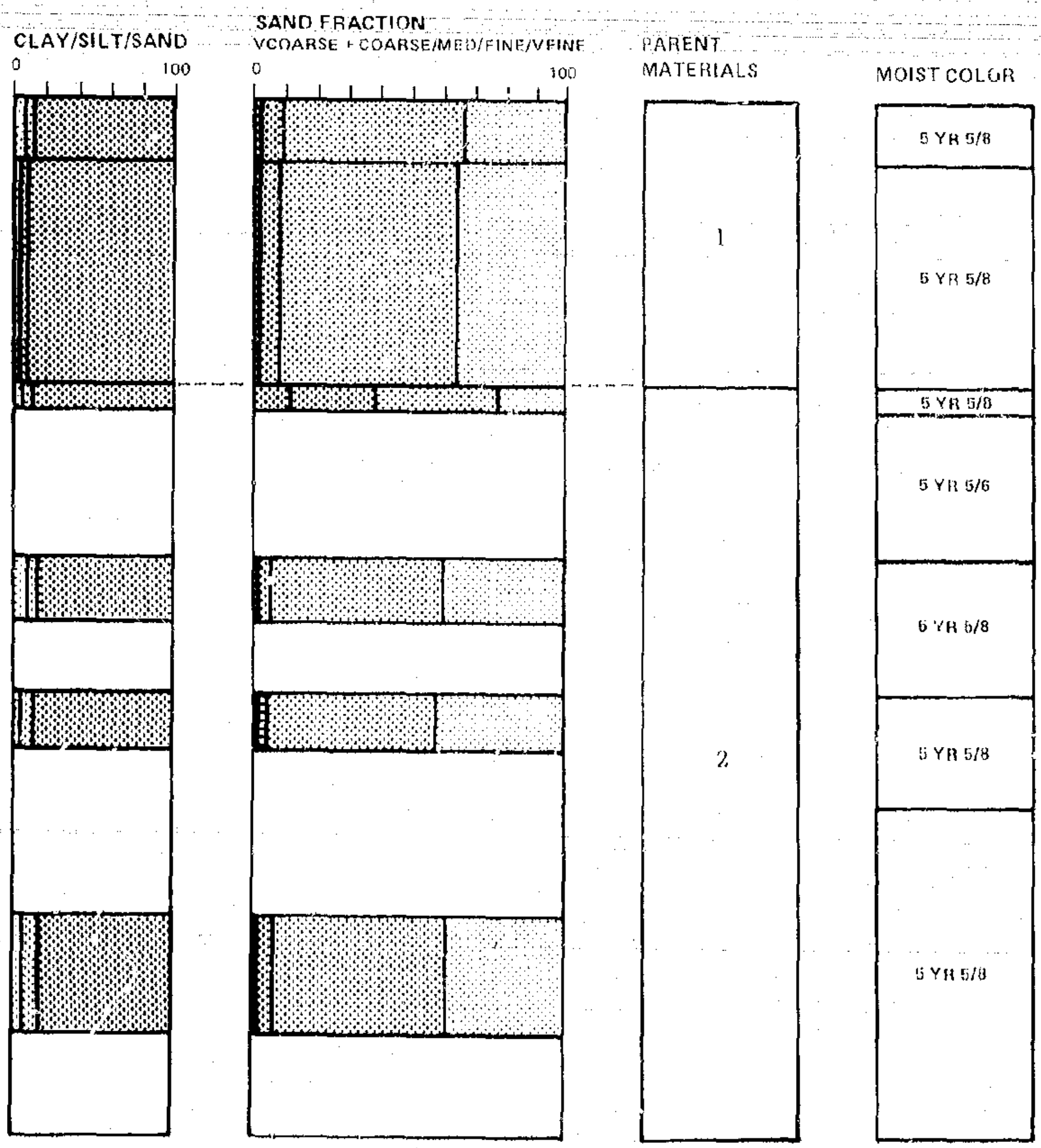

DEPTH
0
FT
0
M
2
1
4
6
2
8
10
3
12
4
14
SOIL HORIZONS
K2m
C1ca
2K21mb
2K22mb
2K3mb
2C1cab
2C2cab
PERCENT CaCO3
0
50
PERCENT CLAY
0
50



ANTELOPE VALLEY SOIL PROFILE
LOCALITY 12
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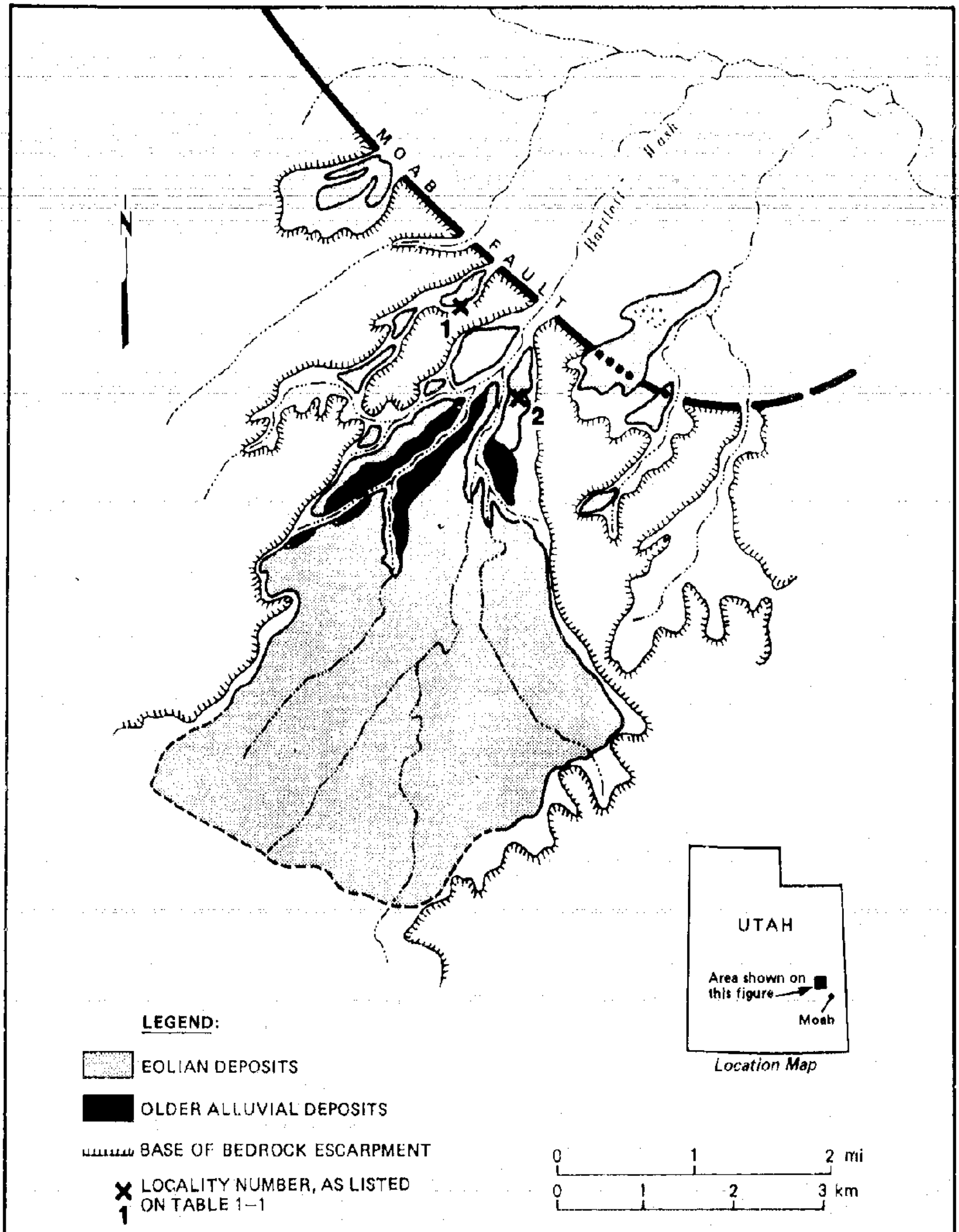
Table 4-19. Thermoluminescence Dates From Green and Colorado River Terraces

Locality	Site	Approximate Height Above Present Stream Level: Meters	Feet	TL Date (10^3 years BP)	TL Lab No.	Comments
4	Sec. 14, T26S, R16E-1	330	1,080	134 ± 19.3	459	Keg Knoll, Green River terrace. Deposits have reversed(?) paleomagnetic stratigraphy.
74	Sec. 32, T38S, R11E-1	200	655	307 ± 39.3	460	Halls Crossing; Colorado River terrace
76	Sec. 35, T38S, R11E-1	250	800	140 ± 11.8	461	Halls Crossing; Colorado River terrace



LOCATION OF SAMPLE LOCALITIES, BARTLETT WASH AND VICINITY

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Figure 4-23

for the tusk. Further study of the origin and age of these deposits would be of interest to any future evaluation of fault activity in the salt anticline belt.

4.2.2 Gibson Dome Area and Vicinity, Localities 32 to 39

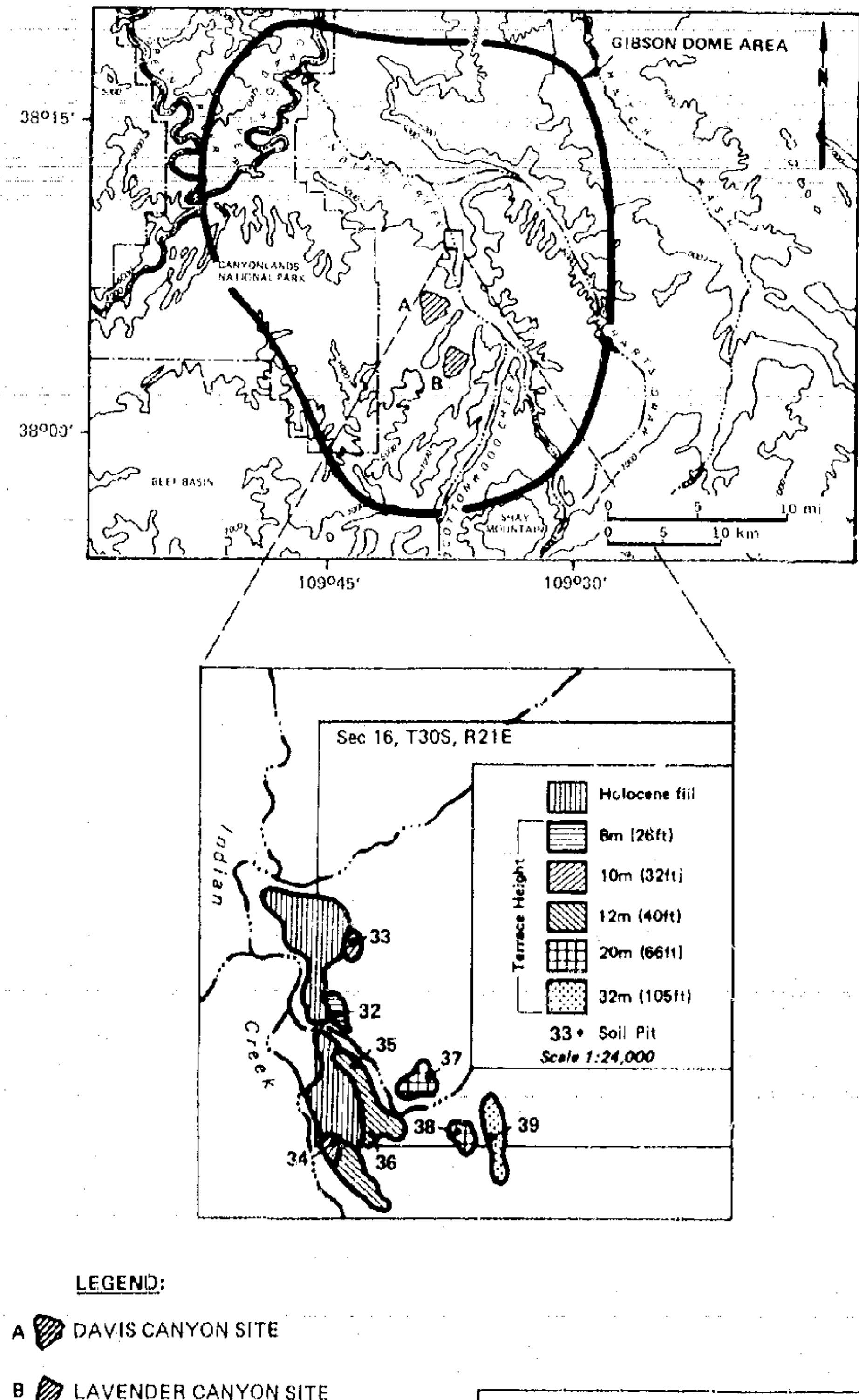
Initial project studies of Quaternary deposits in the Gibson Dome area were reported in WCC (1982a, Vol. II, pp. 4-1 to 4-14). Since then, the pedogenic data for the Indian Creek terraces (Figure 4-24) have been reevaluated and TL dates have been received for these terrace deposits. In addition, further field studies have been conducted in Canyonlands National Park, to the west of the Gibson Dome area. This most recent field work addressed the identification of chronostratigraphic units in Holocene deposits exposed in Salt Creek, and the history of graben development in the Needles Fault zone, discussed in Section 2.5 and Chapter 3, respectively.

A suite of fluvial terraces along Indian Creek was selected for detailed examination of the change in soil properties with age in the Gibson Dome area, on the basic assumption that the age of the terrace deposits is directly proportional to the height of the gravel-capped strath terraces above present stream level. The Quaternary deposits consist of a veneer of gravel 1.2 to 2.1 m (4 to 7 ft) thick, overlain by 0.1 to 0.9 m (0.4 to 3.1 ft) of fine-grained deposits. The alluvial veneer overlies sandstone and shale bedrock of the Cutler Formation.

4.2.2.1 Recalculation of Pedogenic Carbonate Content of Soil Profiles, Indian Creek Terraces

The pedogenic carbonate content of soil profiles on Indian Creek terrace gravels (Localities 32 to 39) were initially reported in WCC (1982a, Vol. II, pp. 4-7 to 4-9). In subsequent use of the soil data, a reevaluation of field descriptions of the carbonate morphology at the base of the profiles indicated that very little pedogenic carbonate ($CaCO_3$) is present. Therefore, the relatively high $CaCO_3$ laboratory values measured in the lower parts of most profiles (WCC, 1982a, Vol. V, Figures B-9 to B-16) are believed to reflect the carbonate content of the parent material. Calcite cement in sedimentary clasts in the gravel is the most likely source of this carbonate. Pedogenic carbonate content of all the soil profiles was therefore recalculated using higher $CaCO_3$ values for the parent material (Table 4-20). The recalculation results in a lower pedogenic $CaCO_3$ content for the terrace deposits (Figure 4-25), which makes the soil ages based on constant influx rates (Figure 4-26) younger than previous calculations indicated.

The recalculated values for pedogenic carbonate reveal a slightly different relationship between terrace height and carbonate content (Figure 4-25) from that presented in WCC (1982a, Vol. II, Figure 4-11). With the exception of data points 1 and 4, the recalculated data (Figure 4-25) show a more linear relationship between the two variables than did the previous calculations. However, separation of the terraces into three age groups (WCC, 1982a, Vol. II, p. 4-8) is not so apparent with the new data (Figure 4-25). The highest terrace (32 m [105 ft]) remains distinctly separate from the others with the exception of one of the 12-m (40-ft) terraces, for which the measured



LOCATION OF SAMPLE LOCALITIES, INDIAN CREEK TERRACES

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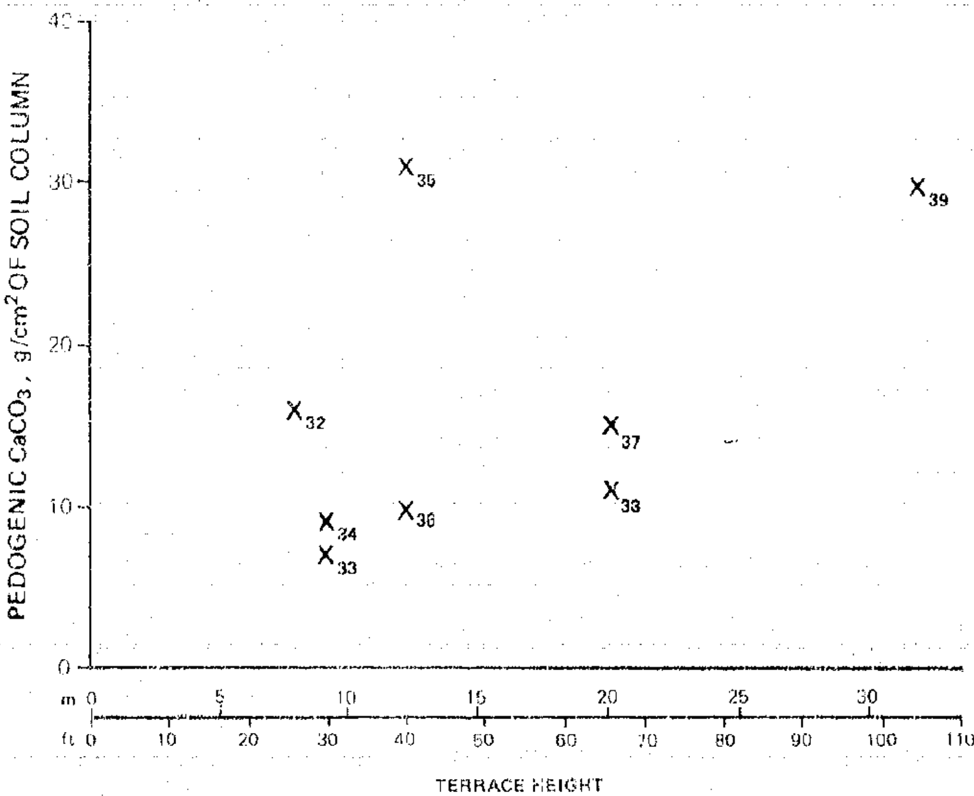
Figure 4–24

Table 4-20. Recalculated Values for Calcium Carbonate Accumulation in Soils on Gibson Dome Gravel Terraces

Profile No.	Height (m)	Locality	No. of Samples Analyzed	$CaCo_3$ in $\leq$2mm Fraction (g/cm^2)	Estimated $CaCO_3$ Content of Parent Material $\leq$2mm fraction (%)	Estimated $CaCO_3$ Content of Parent Material $\leq$2mm fraction (g/cm^2)	Total $CaCO_3$ in >2mm fraction (g/cm^2)	Estimated $CaCO_3$ Content of Parent Material >2mm fraction (%)	Estimated $CaCO_3$ Content of Parent Material >2mm fraction (g/cm^2)	Total $CaCO_3$ (g/cm^2)	Estimated Pedogenic $CaCO_3$ (g/cm^2)
8	32	39	9	40.9	14.2	25.1	56.9	27.8	43.0	97.8	30
7	20	38	9	40.1	16.4	30.2	4.8	23.9	3.8	44.9	11
6	20	37	5	35.8	15.1	27.5	24.6	21.0	18.1	60.4	15
5	12	36	9	37.8	15.0	29.8	12.0	23.1	9.9	49.8	10
4	12	35	7	53.0	13.5	31.9	63.4	20.3	53.6	116.4	31
3	10	34	4	21.6	15.3	18.5	13.9	10.1	8.5	35.5	9
2	10	33	7	21.9	14.2	19.7	30.4	21.4	25.8	[illegible]2.3	7
1	8	32	7	28.9	11.3	19.9	53.6	15.7	46.4	[illegible].5	16



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X_{33} SOIL PROFILE NUMBER, NUMBERED SEQUENTIALLY FROM LOWEST TERRACE (X_{32}) TO HIGHEST TERRACE (X_{39})

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RECALCULATED ACCUMULATIONS OF CALCIUM CARBONATE, GIBSON DOME TERRACES Quaternary Topical Report	
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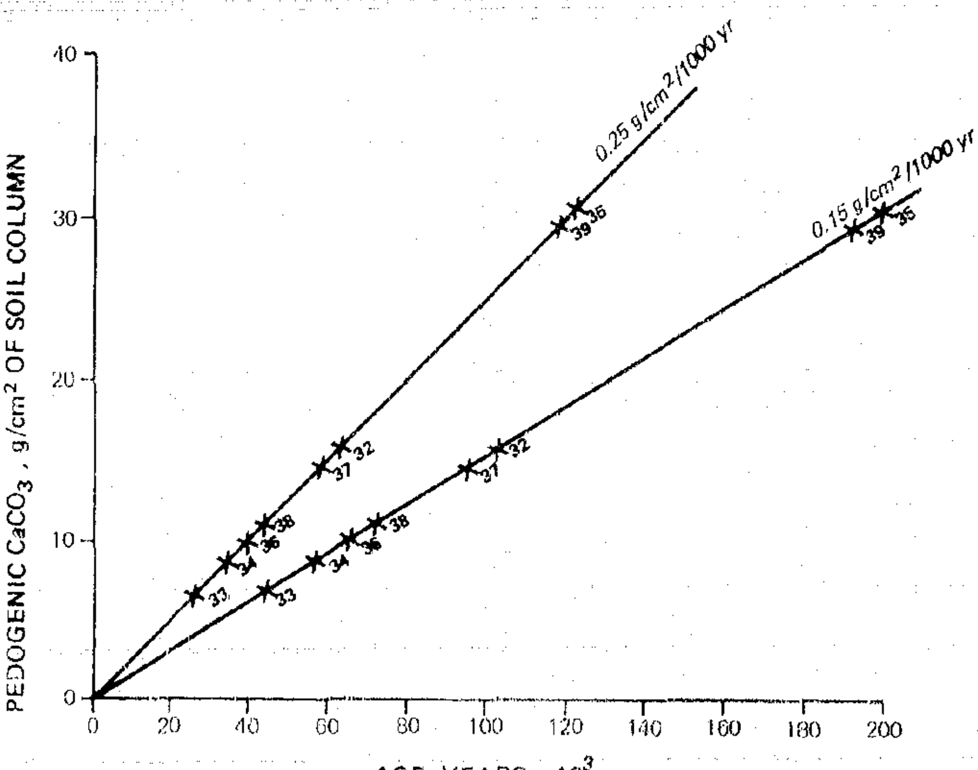

LEGEND:

X_{33} SOIL PROFILE NUMBER, NUMBERED SEQUENTIALLY FROM LOWEST TERRACE(X_{32})TO HIGHEST TERRACE (X_{39})

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AGE ESTIMATES BASED ON CALCIUM CARBONATE CONTENT ASSUMING CONSTANT INFLUX RATES, GIBSON DOME TERRACES Quaternary Topical Report	
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pedogenic carbonate content appears to be equivalent. The new calculations show that, using constant $CaCo_3$ influx rates of 0.15 to 0.25 g/cm/1,000 years, the other terraces are all younger than Placer Creek deposits (130,000 to 200,000 years) (Figure 4-26).

4.2.2.2 Thermoluminescence Dates, Indian Creek Terraces

Laboratory data of soil profiles developed in the Gibson Dome terrace deposits have been interpreted as indicative of pedologic boundaries that are independent of the depositional boundary between the gravel and fine-grained deposits (WCC, 1982a, Vol. II, p. 4-9). Rather than a compound profile, only one soil profile appears to be formed on two or more depositional units at all the Gibson Dome terrace sites. Therefore, the fine-grained and gravel deposits should be of similar age at each terrace site, and the TL dates should generally increase in age with terrace height.

Fourteen TL dates were obtained from eight remnants of five terrace surfaces adjacent to Indian Creek (Table 4-21). Six of the TL dates are for samples of eolian deposits that overlie the gravel; the remaining eight dates are for gravel terrace deposits. The progression of TL dates for deposits underlying successively higher and older surfaces along the Indian Creek is less systematic than in Spanish Valley, and the TL dates tend to be older than the soil carbonate ages (Table 4-21; Figure 4-27). The TL dates generally increase with terrace height; however, the trend is erratic.

Three of the four youngest TL dates (<10,000 years) are from the surficial eolian deposits and were collected within 0.3 m (1 ft) of the ground surface. The fourth date is from the top of the underlying gravel deposits, at a depth of 0.5 m (1.5 ft), between 0.1 and 0.2 m (0.5 ft) below the base of the overlying eolian deposits. All the young dates were derived from the terraces that are 12 m (40 ft) or less in height. These data suggest that some of the uppermost eolian material has only recently been deposited on the terraces within 12 m (40 ft) of present stream level, and that the soil profiles defined in WCC (1982a, Vol. V, Figures B-9 to B-16) are forming in accretionary deposits. This effect is not seen at Localities 37 through 39, where TL dates range from 140,000 to 215,000 years BP for both eolian and gravel samples collected at depths of less than 0.4 m (1.5 ft).

If the TL dates are correct, eolian material has not been deposited and/or retained in any significant amount on the higher terrace surfaces for several tens of thousands of years. Of the terraces examined, the eolian deposits were observed to be thinner on the upper terraces than on the lower deposits, supporting the observation that loose (young) eolian deposits may not be retained on the higher surfaces.

The differences between the age dates obtained for the Indian Creek terraces from the TL and soil carbonate accumulation dating methods could have several causes. Interpretation of the soil carbonate data assumes that the amount of carbonate in the parent material can be accurately determined from laboratory data, and that $CaCO_3$ has not been removed from the profile by any means. The TL dates may be affected by gamma radiation from clasts in the gravel. Uranium-rich sandstone bedrock units are known to occur in the drainage basin upstream from the Indian Creek terraces. Because the samples

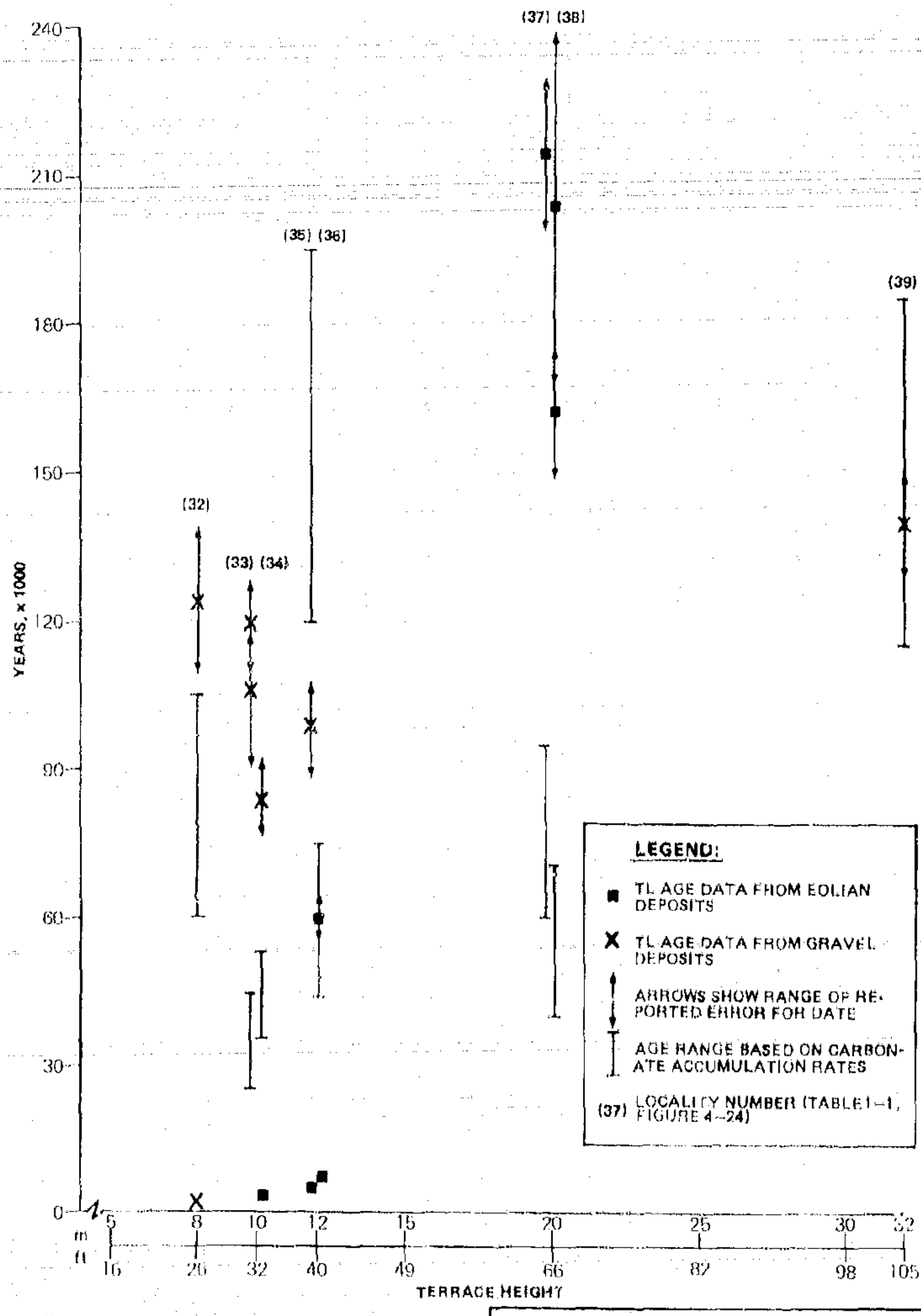
Table 4-21. Comparison of Calcic Soil Ages and Thermoluminescence Dates, Gibson Dome
(Page 1 of 2)

Geologic Epoch Age (10^3 years) Probable Correlation	Terrace Height meters	Terrace Height feet	Locality(a)	Site	Type of Deposit TL Sample(b)	TL date(c) (10^3 yr)	TL Lab No. (ALPHA-)	Soil $CaCO_3$ age (10^3 yr)(d)	Soil Profile No.(e)	Comments
Late Pleistocene (ca 10 to ca 130) Beaver Basin Formation	8	26	32	Sec. 16, T30S, R21E-7	G	1.96 ± 0.2 "too inhomogeneous"	542 ---	65 - 105	1	Duplicate samples collected at between 0.1 and 0.2 m (0.5 ft) below eolian cover.
						124 ± 13.5	450			Sampled horizon is uncertain.
	10	32	33	Sec. 16, T30S, R21E-8	G	106 ± 13.3 118 ± 8.22	452 451	30 - 45	2	Duplicate samples collected at between 0.1 and 0.2 m (0.5 ft) below eolian cover.
	10	32	34	Sec. 16, T30S, R21E-6	E	3.6 ± 0.29	541	35 - 60	3	Collected at depth of 0.3 m (1 ft).
					G	84.1 ± 6.23	449			Collected at between 0.1 and 0.2 m (0.5 ft) below eolian cover.
	12	40	35	Sec. 16, T30S, R21E-5	E	4.01 ± 0.31	540	125 - 205	4	Collected at depth of 0.2 m (0.7 ft)
						100 ± 8	448			Collected at between 0.1 and 0.2 m (0.5 ft) below eolian cover.
	12	40	36	Sec. 16, T30S, R21E-4	E	8.12 ± 0.74	446	40 - 65	5	Collected at depth of 0.2 m (0.7 ft).
					E	59.8 ± 4.45	447			Collected at depth of 0.5 m (1.6 ft). No TL samples collected from gravel.

Table 4-21. Comparison of Calcic Soil Ages and Thermoluminescence Dates, Gibson Dome
(Page 2 of 2)

Geologic Epoch Age (10^3 years) Probable Correlation	Terrace Height meters	Terrace Height feet	Locality[a]	Site	Type of Deposit TL Sample[b]	TL date[c] (10^3 yr)	TL Lab No. (ALPHA-)	Soil $CaCO_3$ age (10^3 yr)[d]	Soil Profile No.[e]	Comments
	20	66	37	Sec. 16, T30S, R21E-3	E	215 ± 16.6	445	60 - 100	6	Collected at depth of 0.3 m (1 ft). No TL samples collected from gravel.
	20	66	38	Sec. 16, T30S, R21E-2	E	204.2 ± 34.43	551	45 - 75	7	Collected at depth of 0.2 m (0.7 ft).
					E	163 ± 12.4	444			Collected at depth of 0.4 m (1.5 ft). Sample order may have been interchanged. No TL sample collected from gravel.
Middle Pleistocene (ca 130 to ca 730) Placer Creek Formation	32	105	39	Sec. 16, T30S, R21E-1	G	140 ± 9.7 "too inhomogeneous"	443 ---	120 - 200	8	Duplicate samples collected 0.2 to 0.3 m (0.7 to 1.0 ft) below eolian cover.

(a) Refer to Table 1-1 and Figure 1-1.
(b) G = Alluvial gravel; E = eolian deposit.
(c) BP = Years before 1950 A.D.
(d) Assumes a $CaCO_3$ influx rate of 0.15 to 0.25 g/cm^2/1,000 years.
(e) Refers to soil profiles in Appendix B, WCC (1982a, Figures B-9 through B-16).



COMPARISON OF AGES DERIVED FROM SOIL CARBONATE ACCUMULATIONS AND THERMOLUMINESCENCE ANALYSES, INDIAN CREEK TERRACES, GIBSON DOME

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Figure 4–27

were all collected at least 1 to 1.2 m (3 to 4 ft) above the bedrock surface, it is not possible that the local bedrock has enhanced the radioactive background of the samples, causing TL ages to be systematically older, because gamma radiation can travel only approximately 30 cm (12 in) through the deposits (Wintle, 1983). It is more likely that uranium-rich sedimentary clasts occur within the gravel, and that when these have been within 30 cm (12 in) of the sampling site, they have produced a higher radioactive background for the collected samples. Neither information on the variability in the radioactive content of the different gravel types, nor the variability in the percentage of sedimentary clasts in the various terrace deposits is presently available, so it has not been possible to verify this hypothesis.

4.2.3 Elk Ridge Area and Vicinity

Eolian deposits are widespread on upland surfaces in the Elk Ridge area and adjacent to the Abajo Mountains (WCC, 1982a, Vol. III). At several localities, young deposits overlie one or more buried soils formed on older eolian material. However, the patterns of soil development and preservation of older deposits on bedrock surfaces are complex. Parent material variability, localized erosion and deposition, and topographic position all have important effects on the soil profiles seen on these surfaces.

East of the Elk Ridge area, remnants of gravel fans flanking the Abajo Mountains occur as pediments that are preserved on stream interfluves in the vicinity of Blanding and Monticello. The gravel grades to finer-grained deposits on the distal portions of the fans, and an eolian cover commonly overlies the fan deposits. The eolian/gravel sequence also typifies Colorado River terraces above Lake Powell, west of the Elk Ridge area.

4.2.3.1 Elk Ridge Area

In the Elk Ridge area, eolian deposits blanket a vast surface developed on Cedar Mesa Sandstone (WCC, 1982a, Vol. III, Figure 5-4). Detailed sampling and laboratory analyses of soil profiles in eolian deposits were conducted for this study at six backhoe pits (Localities 57 to 62) excavated at the Elk Ridge No. 1 (ER-1) borehole location*, and at a natural arroyo exposure on Dry Wash (Locality 66), 10 km (6 mi) east of the ER-1 site (Figures 1-1 and 4-28). The ages of the deposits at both locations were evaluated by TL analysis. In addition, mollusk shells were collected at the Dry Wash site for amino acid analysis.

Other locations in the Elk Ridge area where age data were derived are also described in this section. These include Locality 65 on Dry Wash and Locality 79 near Comb Wash, where mollusk shells were collected for amino acid analyses; Locality 67, also on Dry Wash, where dates were derived by radiocarbon, TL, and amino acid analyses; and Locality 78, near the mouth of Mule Canyon where age estimates were based on radiocarbon and amino acid analyses (Figure 4-28).

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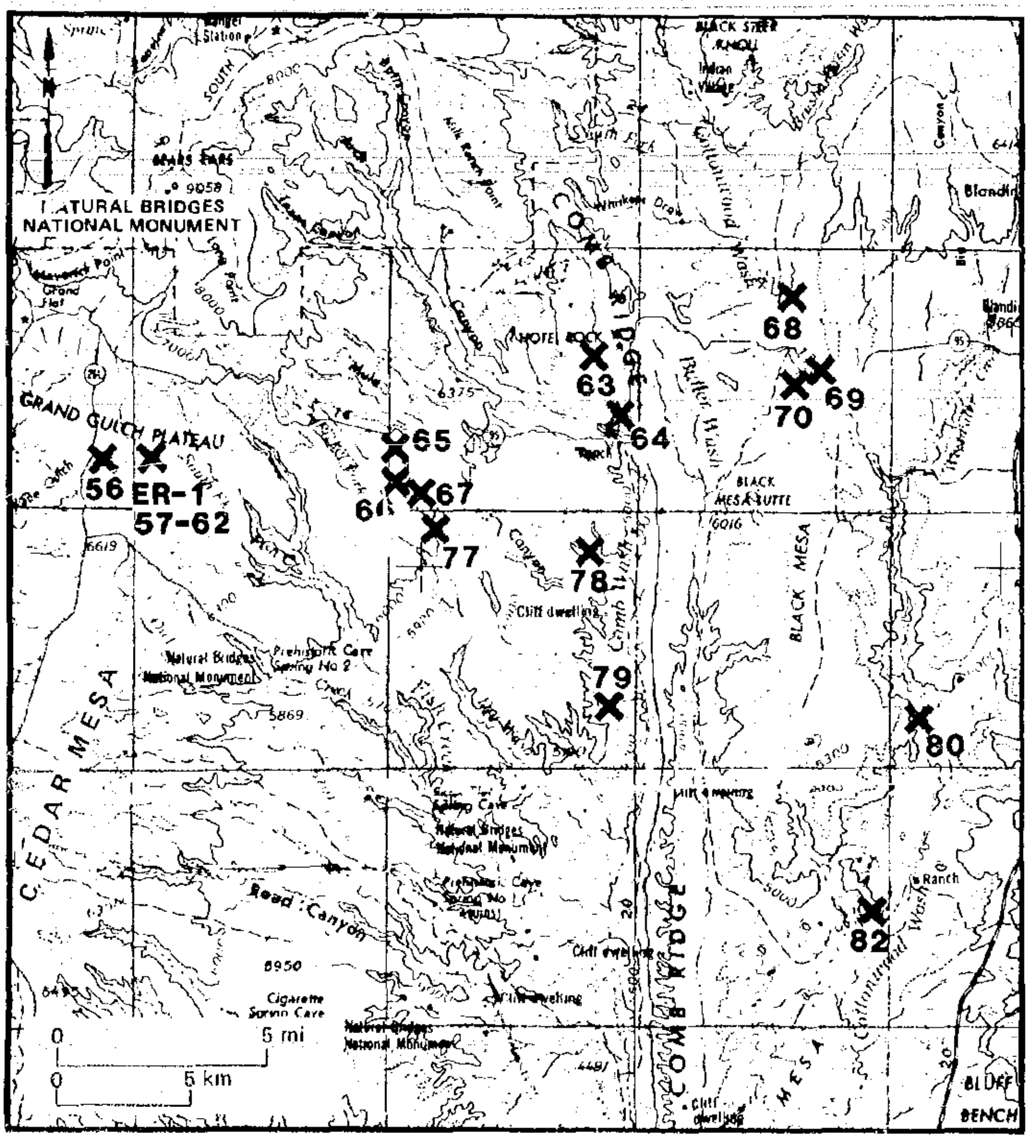
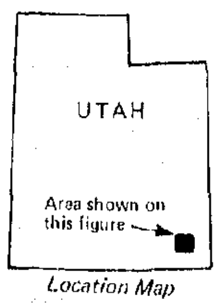
* The ER-1 borehole was drilled by WCC as part of the Paradox Basin studies.



LEGEND:

✕ 56 LOCALITY NUMBER, AS LISTED ON TABLE 1–1



Location Map

LOCATION OF SAMPLE LOCALITIES, ELK RIDGE AREA

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Figure 4–28

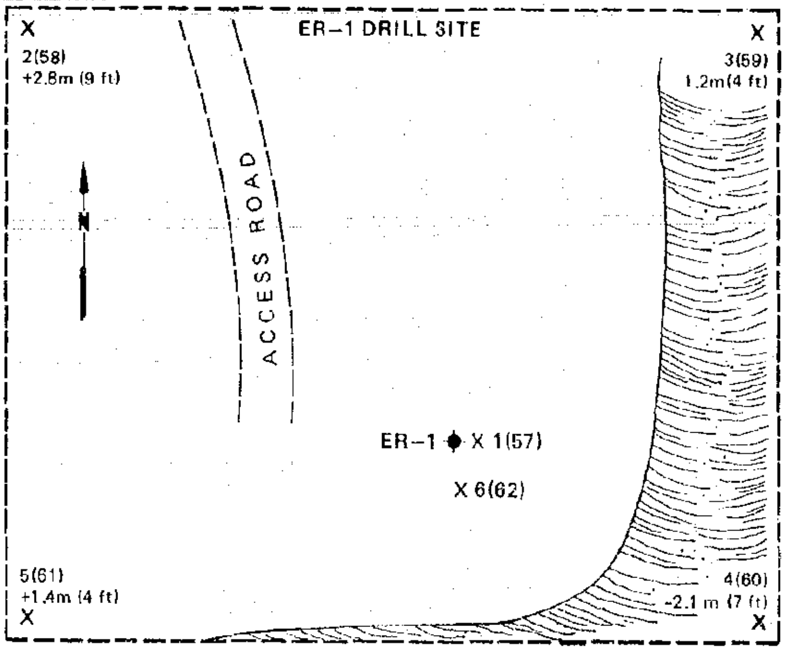
4.2.3.1.1 Elk Ridge No. 1 Site, Localities 57 to 62. Eolian deposits examined at Localities 57 to 62 at the ER-1 site (Figure 4-29) consist of more than 2 m (6 ft) of massive loam to sandy loam (Figures 4-30 through 4-34). The younger deposits generally contain more silt than the underlying older deposits, which are sandier. The sand fraction is predominantly fine and very fine sand.

The eolian material overlies the sandstone bedrock of the Cedar Mesa Sandstone. Profiles 4 and 5 (Localities 60 and 61), at the southern end of the site, are formed on white calcareous arenitic sandstone, whereas Profile 3 (Locality 59) is underlain by red silty sandstone. The bedrock contact is difficult to distinguish in Profiles 1 and 2 (Localities 57 and 58) because the textures of bedrock and eolian deposits are similar, and because relict rock structure is not visible. However, at least 1 m (3 ft) of relief is present on the bedrock surface beneath the eolian deposits. The similarity of the eolian deposits with the underlying bedrock suggests that exposed outcrops of the Cedar Mesa Sandstone may be the source of the windblown material.

At the ER-1 site, all five soil profiles (because of their close proximity, soil data from Pits 1 and 6 [Localities 57 and 62] were combined into Profile 1) display a buried argillic (B) horizon beneath 1 to 2 m (3 to 6 ft) of younger eolian deposits. The buried B horizons exhibit moderate subangular blocky structure; thin clay skins on grains and ped faces range from few to common in abundance. They also show a 5 to 10 percent clay increase relative to the overlying or underlying horizons (Figures 4-30, 4-32, and 4-34). However, because the clay content of the eolian parent material is variable, it is difficult to determine whether some of the clay increase is non-pedogenic.

The carbonate contents of the five profiles are variable (Figures 4-30 through 4-34; Table 4-22). The absence of carbonate in Profiles 4 and 5 (Figures 4-33 and 4-34) may indicate that (1) carbonate was leached from the soil by water draining the shallow swale that trends eastward through this area (Figure 4-29), and that a more pronounced drainage than the present swale may have existed during pre-Holocene time; (2) the eolian deposits at this location are younger than those sampled in the other soil pits; or (3) a low carbonate content exists in the underlying sandstone. Because of the occurrence of the buried argillic horizon at all five soil pits, it is likely that soil carbonate was not deposited in the soil profile, or has been leached from the areas having minimal carbonate buildup in the soil profile.

The remaining three profiles (1, 2, and 3) contain significant carbonate (Figures 4-30 through 4-32; Table 4-22). However, the strong carbonate horizons exposed at the base of Profiles 1 and 3 (Figures 4-30 and 4-32) are interpreted as being due to weathering of an underlying, carbonate-rich silty sandstone. It is known that the Cedar Mesa Sandstone can contain as much as 25 percent $CaCO_3$ cement in the Gibson Dome area (Hite, 1983). Therefore, the carbonate of likely pedogenic origin in these profiles occurs in the soil horizons overlying the lowermost calcic horizon. The upper horizons in Profile 1 contain 18 g/cm^2 of soil carbonate; no significant amount of pedogenic carbonate has accumulated in the upper part of Profile 3.



LEGEND:

X LOCATION OF SOIL PROFILE

5(61) SOIL PROFILE NUMBER (LOCALITY NUMBER)

TOPOGRAPHICALLY LOWER AREA

ELEVATIONS GIVEN RELATIVE TO GROUND SURFACE AT PROFILES 1 AND 6, WHICH WERE EXPOSED IN EXCAVATIONS FOR DRILLING FLUID TANKS AND DRILL RIG, RESPECTIVELY

LOCALITIES ARE SHOWN ON FIGURE 4–28

SOIL PROFILES ARE SHOWN ON FIGURES 4–30 TO 4–34

SCALE

1" = Approximately 50 ft
1 cm = Approximately 6 m

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LOCATION MAP OF SOIL PROFILES DESCRIBED AT ELK RIDGE NO. 1 DRILL SITE

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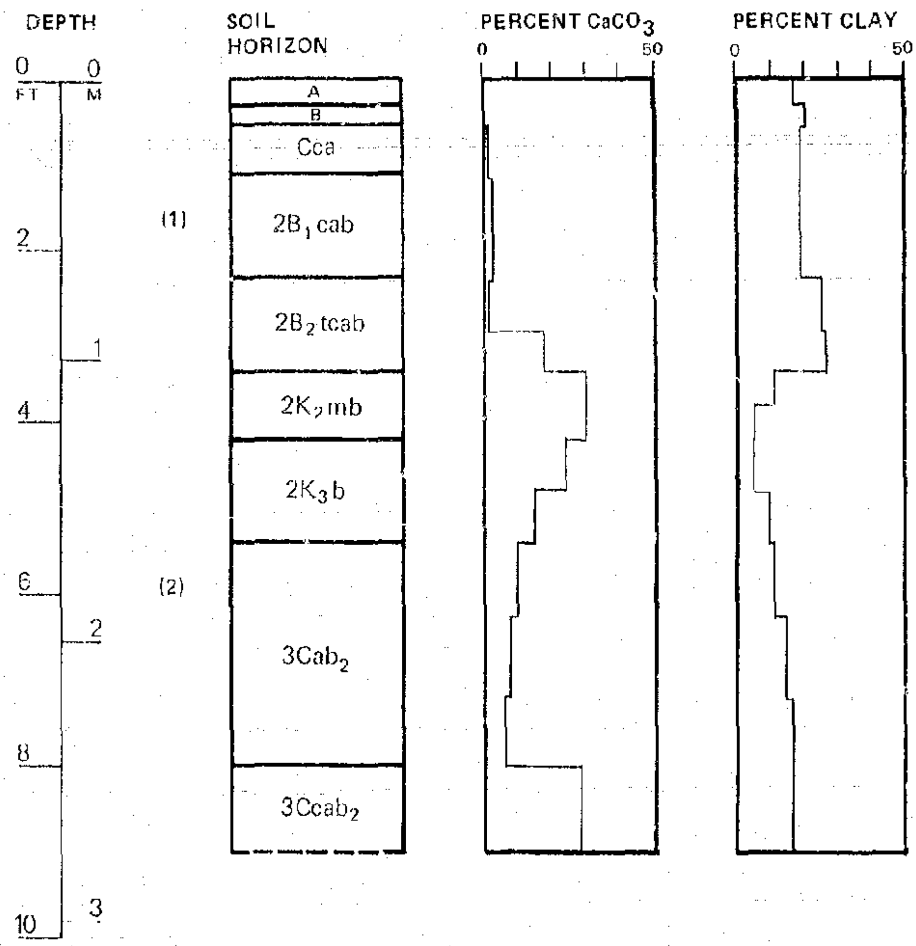
Figure 4–29

Table 4-22. Accumulation of Calcium Carbonate in Soils Formed in Quaternary Eolian Deposits in the Elk Ridge Area

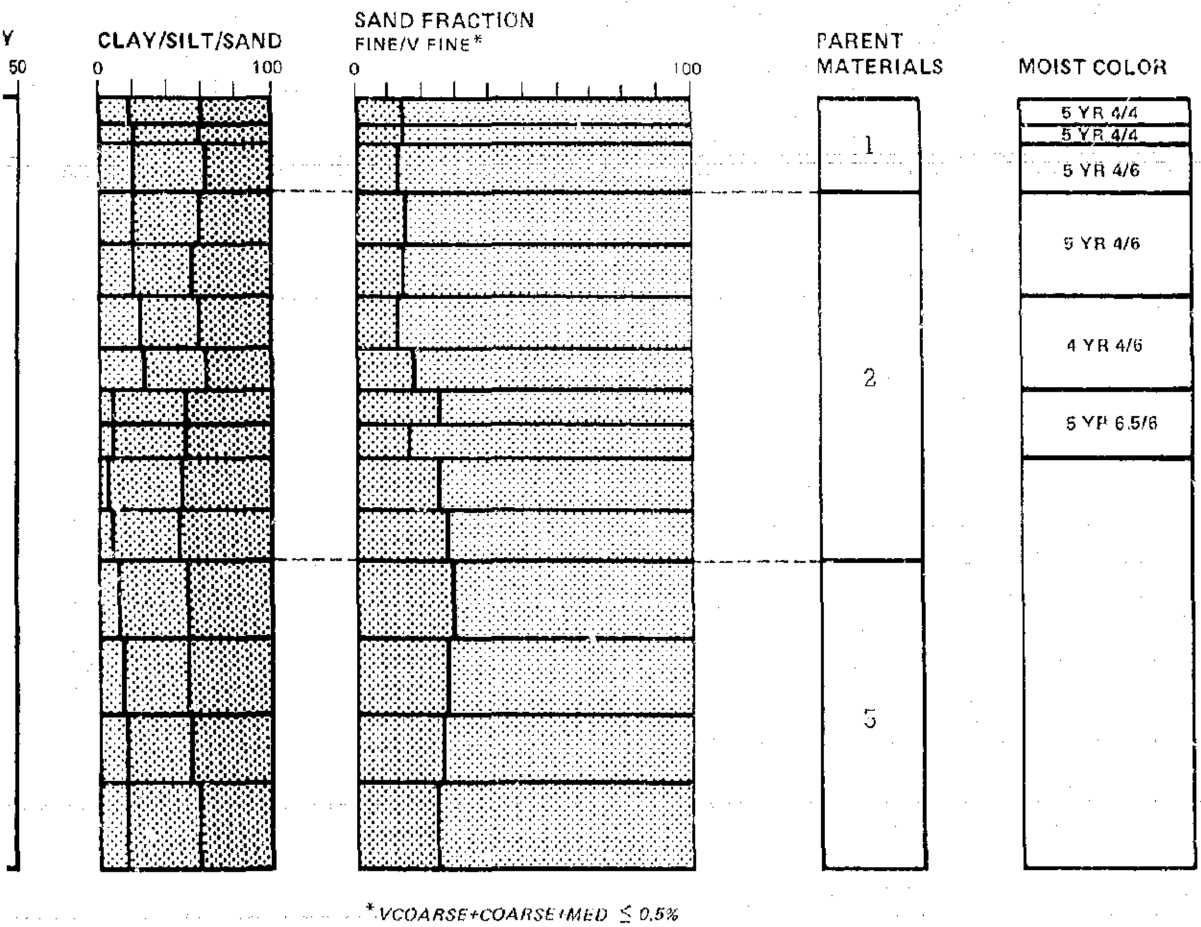
Locality	Site	Portion of Profile	No. of Samples Analyzed	Total $CaCO_3$ Content (g/cm^2)	Estimated $CaCO_3$ Content of Original Parent Material (%)	(g/cm^2)	Estimate Pedogenic $CaCO_3$ (g/cm^2)
EOLIAN DEPOSITS							
57, 62	ER-1 Borehole Site Sec. 30, T37S, R19E Profiles 1,6	Total	14	51.5	5.5	22.6	28.9
		Upper soil bove 3C2cab	13	38.6	5.5	20.2	18.1
58	Profile 2	Total	11[a]	28.1	2.9	13.8	14.3
59	Profile 3	Total	11[a]	92.3	5.2, 12.0[b]	27.6	64.7
		Upper soil above 2Kmb	9[a]	8.6	5.2	13.1	(c)
60	Profile 4	Total	11[a]	--	--		(c)
61	Profile 5	Total	12[a]	--	--		(c)
66	Dry Wash Sec. 31, T37S, R20E-1	Total	13	34.1	1.0	4.8	29.3

(a) Bulk densities estimated from Profile 1.
(b) Parent material for lower soil appears to be more calcareous than upper parent material. Estimated $CaCO_3$ content for bedrock in Profile 3 is based on unpublished data of R. Hite, U.S. Geological Survey, Denver (Hite, 1983).
(c) No significant pedogenic carbonate has accumulated in profile.



THERMOLUMINESCENCE DATES:

(1) 27,9803 ± 2,060 years BP
(2) 44,930 ± 4,030 years BP



ER-1 SITE, SOIL PROFILES 1&6: LOCALITIES 57 AND 62, COMBINED

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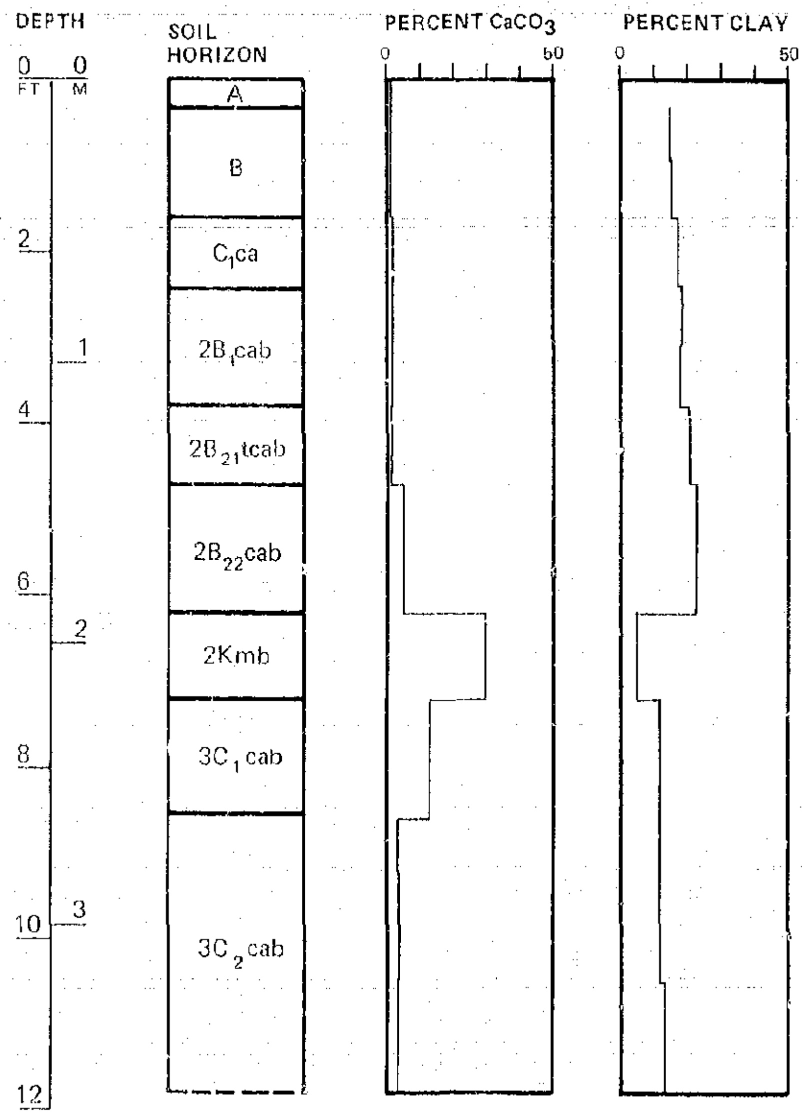
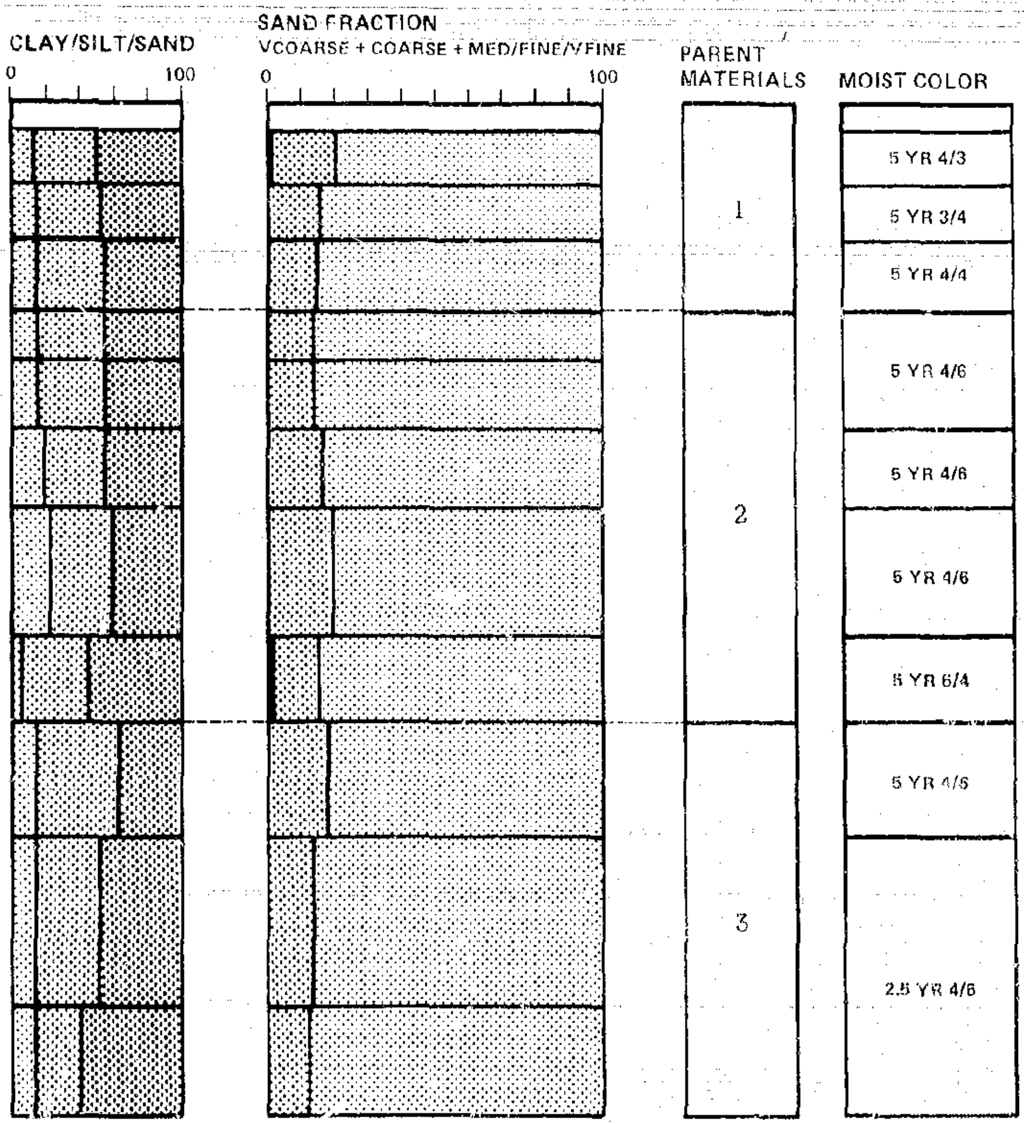
Figure 4-30


DEPTH
0
FT
0
M
2
1
4
6
2
8
10
3
12
SOIL
HORIZON
A
B
C_1ca
$2B_1cab$
$2B_{21}tcab$
$2B_{22}cab$
2Kmb
$3C_1$ cab
$3C_2$ cab
PERCENT $CaCO_3$
0
50
PERCENT CLAY
0
50



ER-1 SITE, SOIL PROFILE 2: LOCALITY 58

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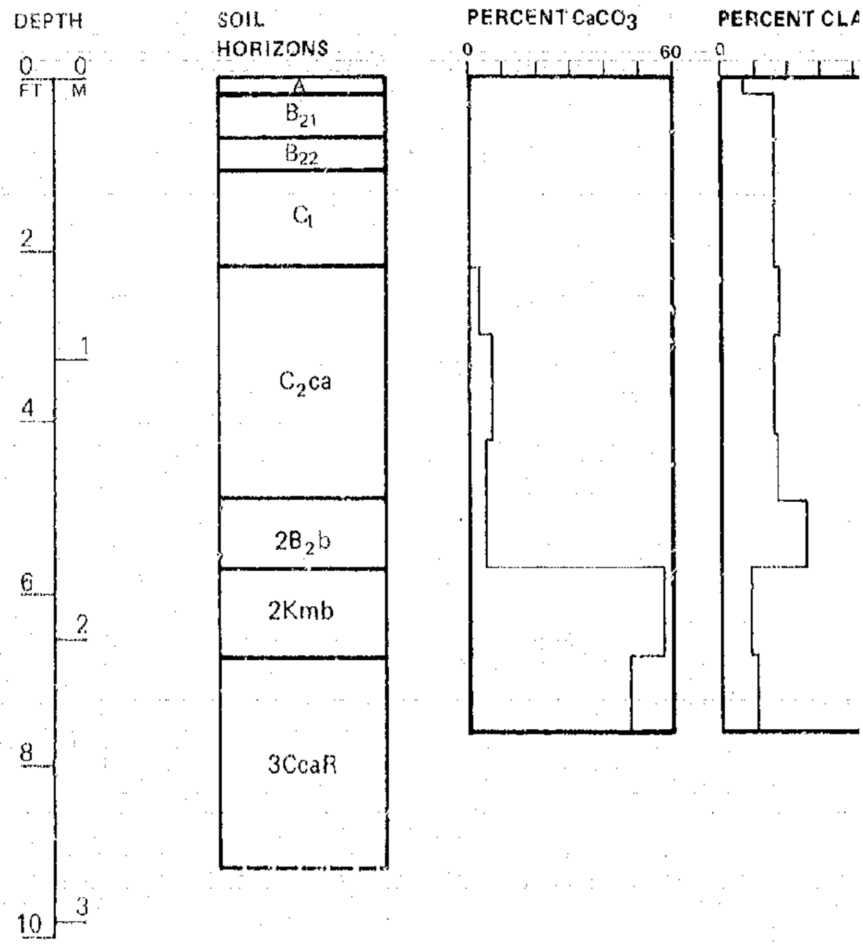
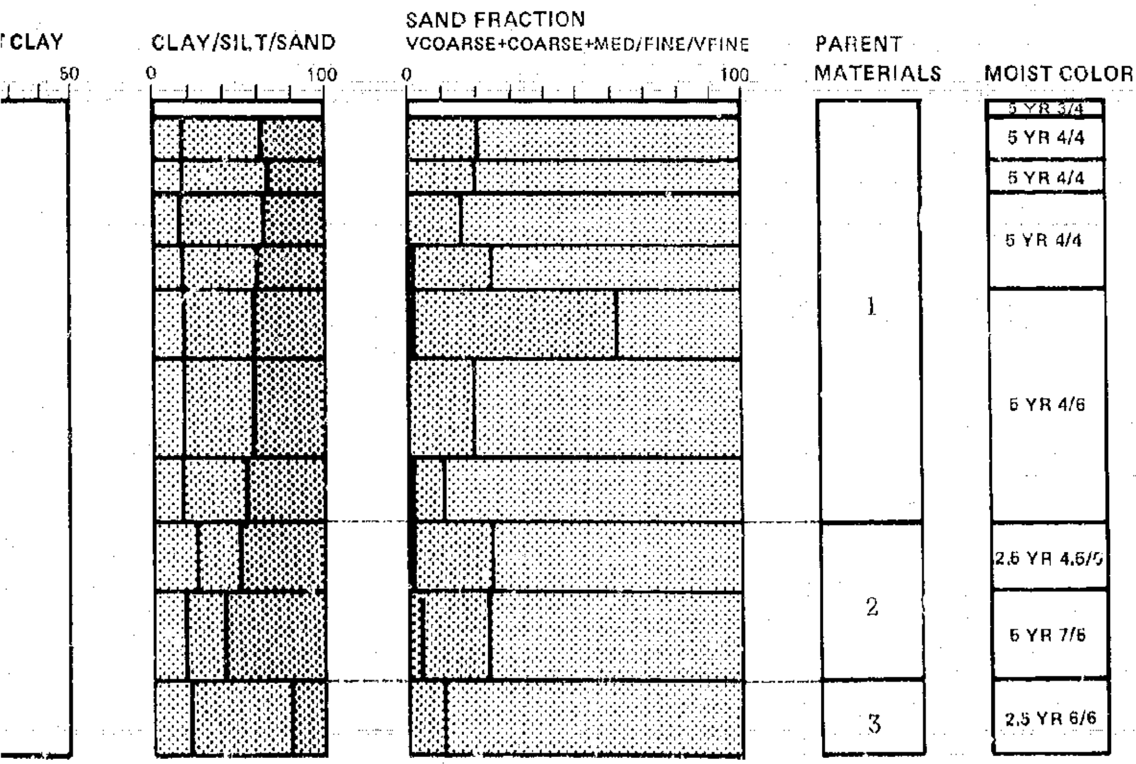
Figure 4-31


DEPTH
0
FT
0
M
2
1
4
6
2
8
10
3
SOIL HORIZONS
A
B_{21}
B_{22}
C_1
C_2ca
$2B_2b$
2Kmb
3CcaR
PERCENT $CaCO_3$
0
60
PERCENT CLA
0

LOG 1563



ER-1 SITE, SOIL PROFILE 3: LOCALITY 59

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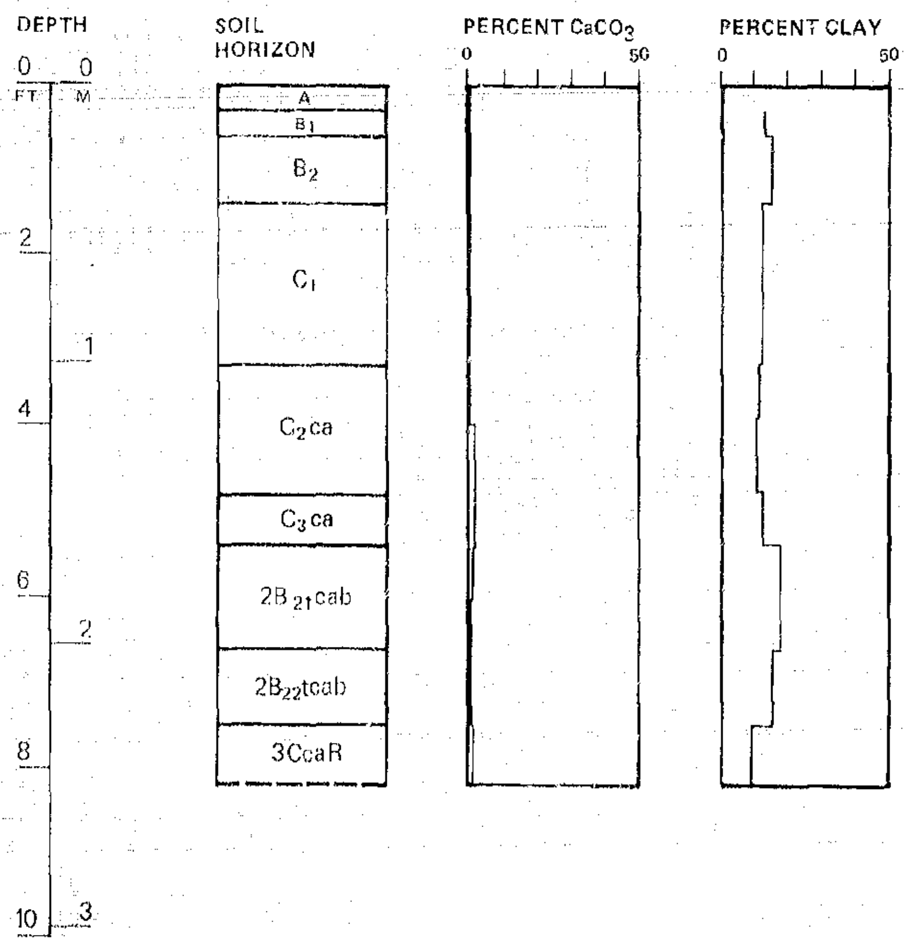
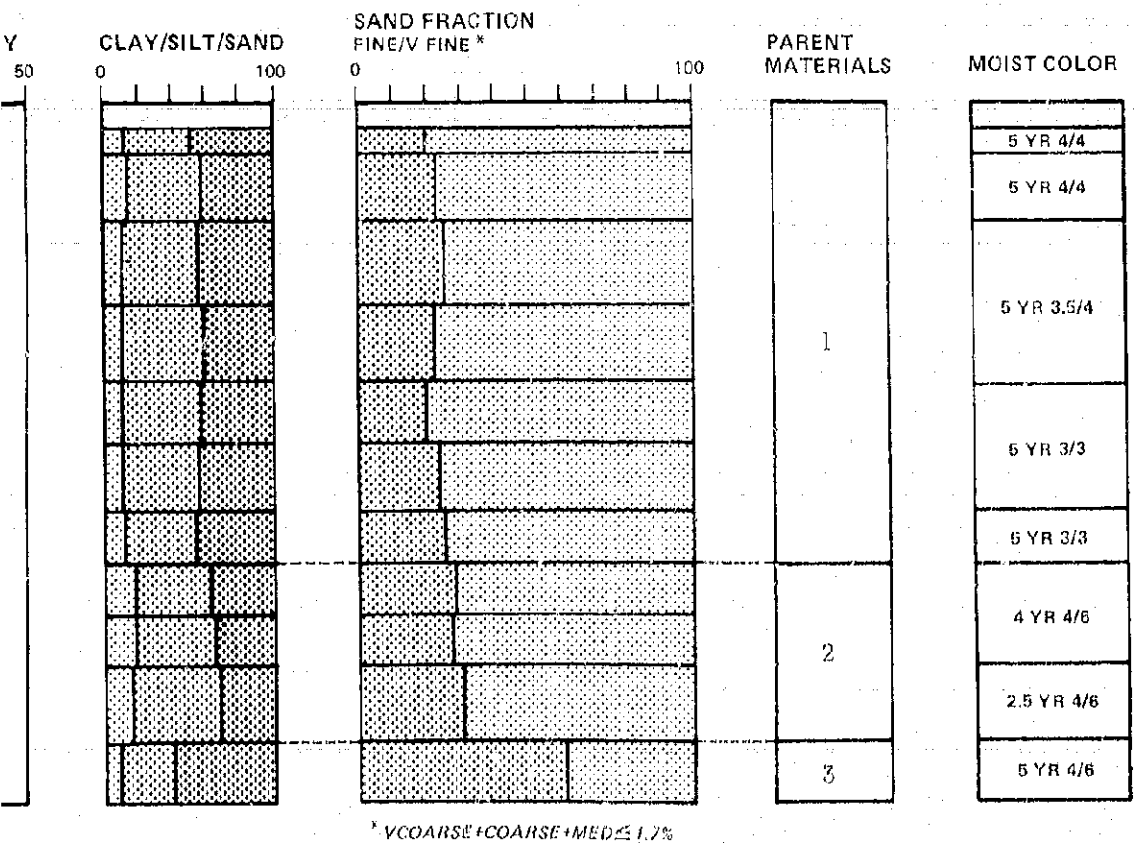
Figure 4-32


DEPTH
FT
M
0
2
4
6
8
10
1
3
SOIL HORIZON
A
B_1
B_2
C_1
C_2ca
C_3ca
$2B_{21}$cab
$2B_{22}$tcab
3CcaR
PERCENT $CaCO_3$
0
50
PERCENT CLAY



ER-1 SITE, SOIL PROFILE 4: LOCALITY 60

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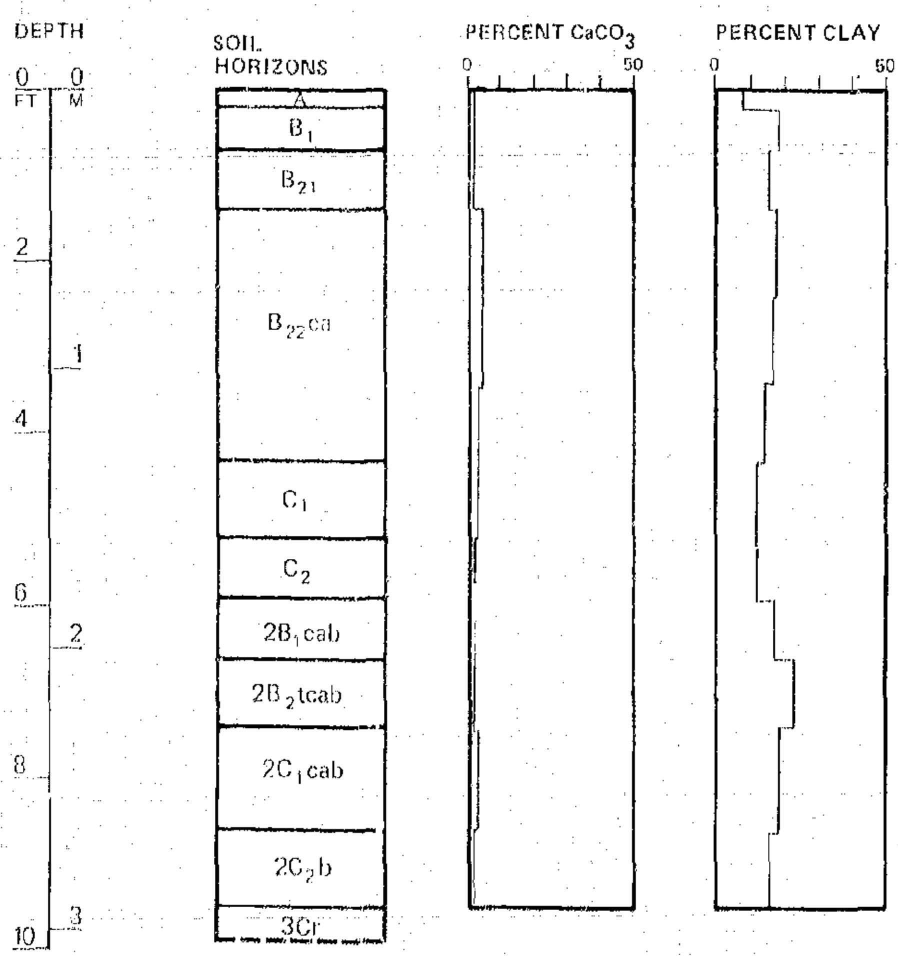
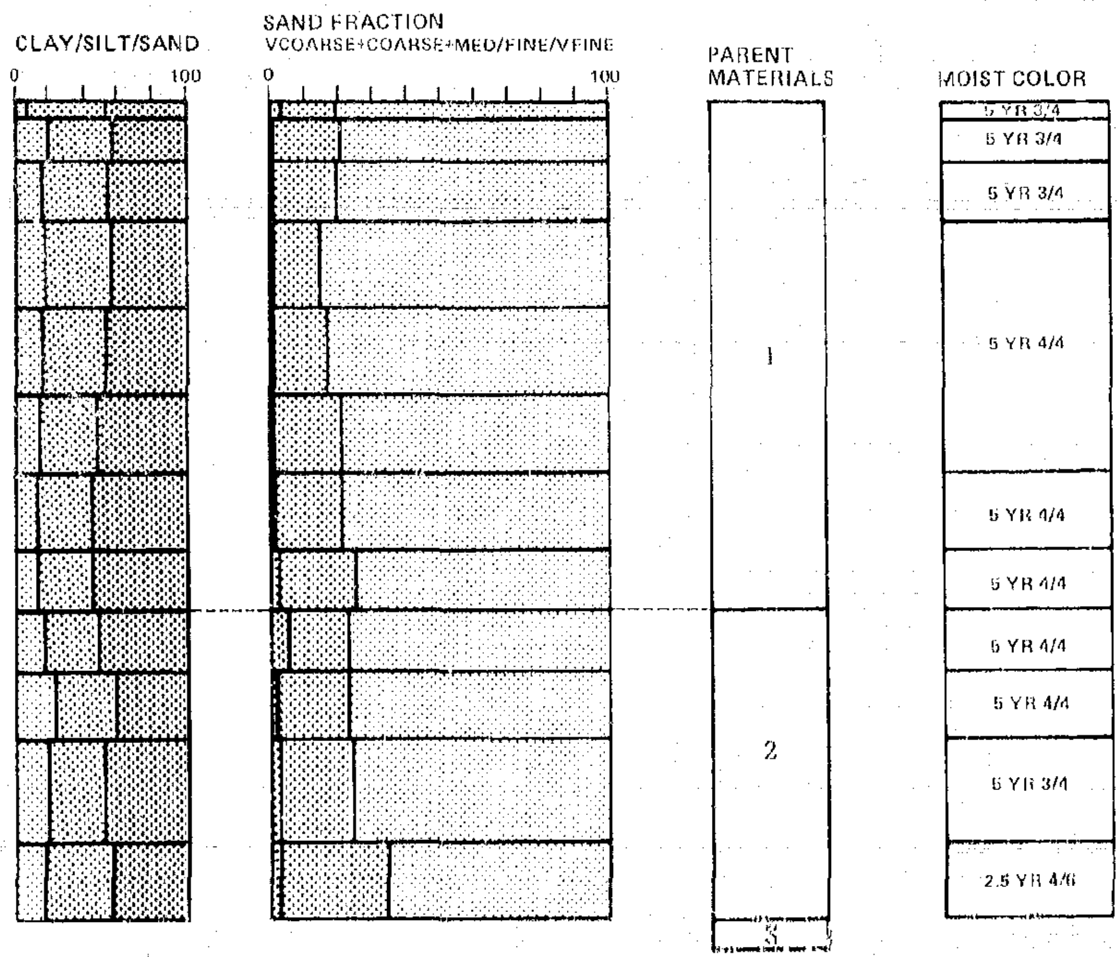
Figure 4-33


DEPTH
0 FT
0 M
2
1
4
6
2
8
10
3
SOIL HORIZONS
A
B_1
B_{21}
$B_{22}ca$
C_1
C_2
$2B_1cab$
$2B_2tcab$
$2C_1cab$
$2C_2b$
3Cr
PERCENT $CaCO_3$
0
50
PERCENT CLAY
0
50



CR-1 SITE-SOIL PROFILE 5: LOCALITY 61

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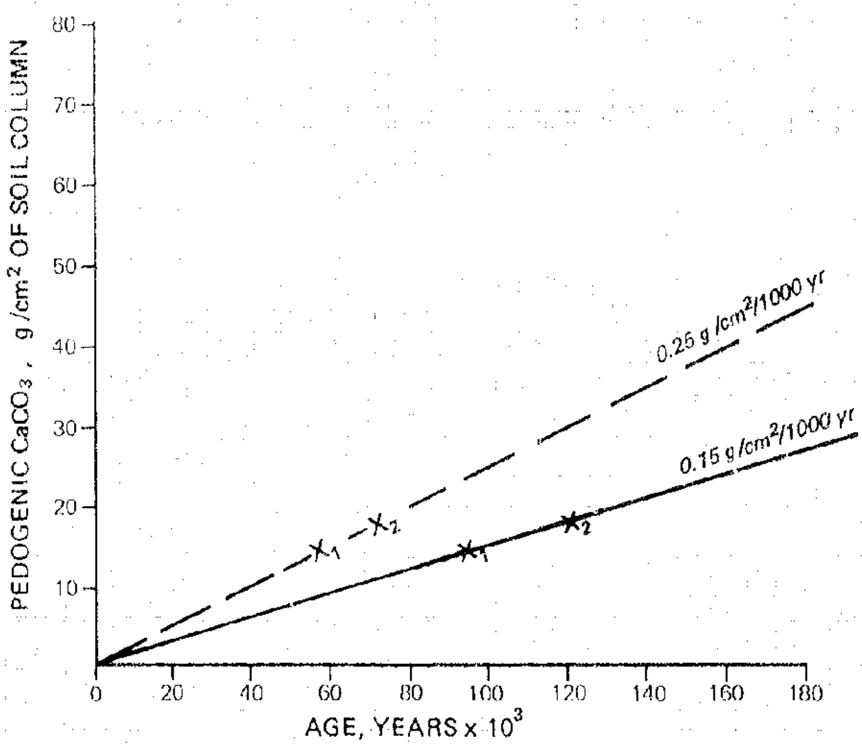
Figure 4-34

Therefore, of the five soil profiles described at the ER-1 site, only Profiles 1 and 2 are interpreted as containing significant pedogenic carbonate. Stage III carbonate morphology is present in K horizons in Profile 1 and Profile 2, which contain, respectively, 18 and 14 g/cm^2 of pedogenic $CaCO_3$ in the soil column. This soil is interpreted as having formed on a buried eolian deposit, and provides a means of estimating the minimum age for the stabilization of the underlying geomorphic surface (Birkeland, 1984). Assuming a minimum long-term $CaCO_3$ accumulation rate of 0.15 g/cm^2/1,000 years, which has been established for other portions of the Paradox Basin (WCC, 1982a, Vol. I), the maximum estimated ages for Profiles 1 and 2 are 120,000 and 95,000 years, respectively (Figure 4-35). Because the Elk Ridge area is higher and more moist than the areas for which long-term accumulation rates have been established, it is likely that estimates based on the influx rates would be minimum ages. Alternatively, if some of the $CaCO_3$ in these two profiles is derived from calcareous bedrock, or if the actual influx rate is higher than the assumed rate, the age of the deposits could be younger than indicated by the above calculations. The buried argillic horizons in all five profiles probably represent at least a few tens of thousands of years of soil development (Shroba, 1982). Therefore, the soil data suggest that eolian deposits have been accumulating on the Cedar Mesa surface for at least 50,000 to 100,000 years.

Two TL samples were collected from deposits above and below the K soil horizon at Profile 1. Derived dates of 27,480$\pm$2,060 years BP and 44,930$\pm$4,030 years (Table 4-23) are stratigraphically consistent and should be older than the soil that subsequently developed on those deposits. However, when the amount of pedogenic $CaCO_3$ (18 g/cm^2) in that part of the profile was measured, an age of 70,000 to 120,000 years was derived for the calcic soil. The buried argillic and calcic horizons also suggest that the deposits are older than the TL dates indicate; the TL dates are assessed to be too young. No additional age data are available for the ER-1 site, but data have been collected from nearby sites in Dry Wash where deposits are considered to be comparable, and are discussed in the following sections.

4.2.3.1.2 Dry Wash, Locality 65. Three calcic soils were described in fine-grained deposits exposed in Dry Wash, approximately 0.5 km (0.25 mi) south of old Highway 95 (Figure 4-28). No soil laboratory analyses were made, but the exposure includes a K horizon with Stage III carbonate morphology. An age of 24,000$\pm$7,000 years was interpreted from mullusk-shell amino acid ratios. The shells were collected at the base of the exposure (Table 4-12). This basal "young" age suggests that the well-developed overlying calcic soil may consist, in part, of stream-deposited carbonate. This interpretation is substantiated by the occurrence of faint carbonate-rich bands 6 to 15 cm (2 to 6 in) thick in the lower 2 m (6 ft) of the exposure. These bands do not appear to be pedogenic in origin and are probably stream or ground-water deposited. Alternatively, the amino acid age assessments may be erroneously low, as they appear to be at other localities, such as Locality 66, described in the following section.



LEGEND:

X_1 SOIL PROFILE NUMBER

LOG 1577 REV. 0–8/23/83	PEDOGENIC CARBONATE VERSUS AGE, ELK RIDGE NO. 1 EOLIAN DEPOSITS Quaternary Topical Report	
	Project No. 17000 **Woodward-Clyde Consultants**	Figure 4-35

Table 4-23. Soil Carbonate and Thermoluminescence Dates From Elk Ridge and White Mesa Areas

Locality	Area	Site	Soil $CaCO_3$ age (10^3 yr)[a]	TL Date (10^3 yr BP)	Depth, TL Sample Meters	Feet	TL Lab Nc (ALPHA -
57,62	Elk Ridge	Sec. 30, T37S, R19E-1,6 combined	115 - 195[b]	27.48 ± 2.06	0.7	2	543
			75 - 125[c]	44.93 ± 4.03	1.8	6	544
58	Elk Ridge	Sec. 30, T37S, R19E-2	55 - 95				
59	Elk Ridge	Sec. 30, T37S, R19E-3	260 - 430[b] NS[c]				
60	Elk Ridge	Sec. 30, T37S, R19E-4	NS[c]				
61	Elk Ridge	Sec. 30, T37S, R19E-5	NS[c]				
71	White Mesa	Sec. 32, T37S, R22E-1	55 - 95[d]	32.7 ± 2.85	2.3	7.5	454
			30 - 5[e]	24.4 ± 2.3	0.4	1.3	453
72	White Mesa	Sec. 33, T37S, R22E-1	335 - 560	137 ± 10.9[f][h]	3.0	10.0	457
			195 - 320[g]	93.8 ± 7.02[h]	2.1	7.0	456
				46.7 ± 3.95[h]	1.1	3.6	455

Notes: Highly variable values for soil $CaCO_3$ ages may be due to local leaching of $CaCO_3$ from deposits in drainage swales. Localities 58 through 61 are within a 100-m (325-ft) radiu of Localities 57 and 62.
NS means no significant pedogenic carbonate has accumulated in profile.

(a) Soil carbonate age of entire soil column, unless otherwise noted. Estimated age assumes $CaCO_3$ influx rate of 0.15 - 0.25 $g/cm^2/1,000$ years.
(b) Age includes lowermost calcic horizon, which may be developed in weathered bedrock.
(c) Age based on pedogenic $CaCO_3$ accumulated in soil profile above basal calcic horizon.
(d) Age represents total $CaCo_3$ in soil profile; includes calcic soil horizon developed on weathered sandstone bedrock; TL date (ALPHA-454) is from base of profile.
(e) Age based on pedogenic $CaCO_3$ accumulated in eolian deposits overlying calcic soil horizon developed on bedrock. TL date (ALPHA 4-53) is from upper part of profile.
(f) TL date is from base of profile.
(g) Age based on pedogenic $CaCO_3$ accumulated in eolian deposits overlying calcic horizon developed on bedrock.
(h) TL dates from successively younger eolian deposits in exposed sequence.

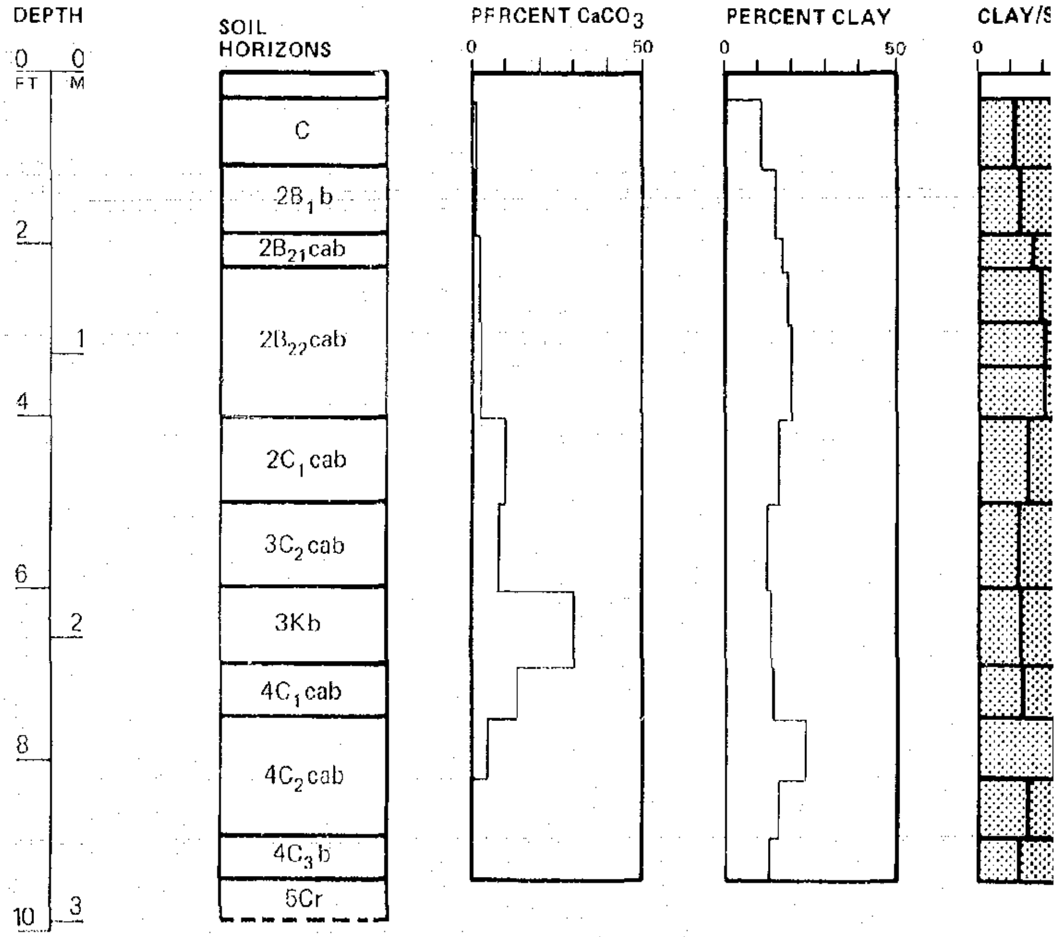
4.2.3.1.3 Dry Wash, Locality 66. A detailed soil description and sampling were completed at a natural exposure on a tributary to Dry Wash (Locality 66) (Figure 4-28). Three eolian units were identified at this exposure on the basis of particle size data (Figure 4-36). The surficial unit is thin and sandy, and overlies a more silty unit. The third unit is more gray in color, and more sandy; the fourth unit has a greater proportion of coarser sand than the overlying unit, and contains mollusk shells in the 4C1cab and 4C2cab soil horizons. The Cedar Mesa Sandstone is exposed at the base of the profile, and the lowermost 15 cm (6 in), which are sandier and coarser-grained than the rest of the section, probably represent weathered sandstone bedrock.

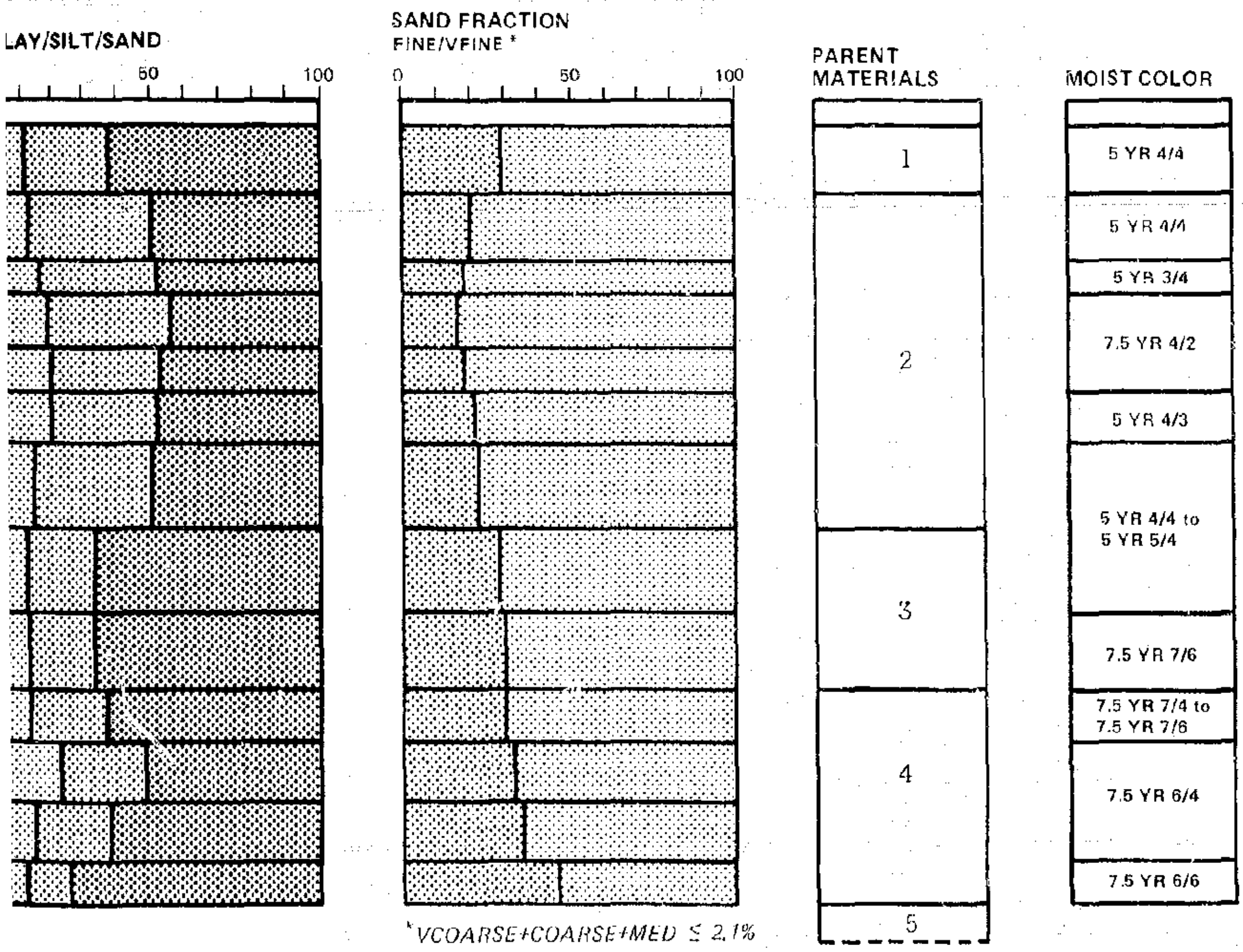
The Dry Wash soil profile has some features that are similar to Profiles 1, 2, and 3 at the ER-1 site. A buried argillic (B) horizon lies beneath the surficial eolian deposits, and a K horizon occurs at greater depth. The argillic horizon exhibits a subangular to angular blocky structure, and a few incipient clay skins were observed on ped faces. These horizons have a 5 to 10 percent clay increase relative to the overlying and underlying horizons (Figure 4-36). The K horizon has a Stage II^+ to III carbonate morphology; in all, the soil profile contains 29 g/cm^2 of pedogenic $CaCO_3$, which is similar to the total amount of $CaCO_3$ measured at Profile 1 at the ER-1 site. Based on calcic soil data, an age estimate is 115,000 to 195,000 years. Mollusk assemblages found at the base of the exposure argue against the K horizon representing top of bedrock. The carbonate content of the weathered sandstone bedrock appears to be minimal at this locality.

Another age assessment of the Dry Wash deposits was based on amino acid analysis of mollusk shells found near the base of the exposure. Interpretation of amino acid ratios derived from the mollusk shells provides a date of 19,000$\pm$6,000 years BP (Table 4-12). The amino acid ratios appear to be of good quality, and the analytical data do not suggest that the sample had been contaminated (McCoy, 1983). The buried argillic horizon, however, argues that the amino acid date represents a minimal age for the deposit. If the shells were 100,000 years old, as the soil data suggest, the measured amino acid ratios indicate that the mean annual temperature would have had to be approximately 20°C (35°F) cooler than at present. Because paleoecological data for the Southwest indicate that temperatures were probably not lower than about 10°C (18°F) below present mean annual temperatures during full glacial maximum (Spaulding et al., 1983), the amino acid data suggest that the calcic soil developed at this site is not totally time-dependent.

On the basis of these age assessments at Locality 66, the deposits exposed in the arroyo cut are assessed to be older than 19,000 years BP, but probably younger than the 115,000 minimal date derived from the soil carbonate data. An alternate explanation for the high $CaCO_3$ content is that some of the carbonate is due to stream deposition.

4.2.3.1.4 Dry Wash, Locality 67. At Locality 67, approximately 1.5 km (1 mi) downstream of Locality 66 (Figure 4-28), samples were collected from a stratigraphic section to compare dates derived by radiocarbon, TL, and amino acid analyses. Sufficient charcoal was disseminated in one thin deposit for submittal of disguised duplicate samples to the radiocarbon laboratory to assess the reproducibility of the ^{14}C data (Tables 1-1 and 4-7). The two derived dates of 9,490$\pm$90 BP (BETA-4414) and 7,840$\pm$700 BP (BETA-6221) are


DEPTH
0
0
FT
M
2
1
4
6
2
8
10
3
SOIL HORIZONS
C
2B1b
2B21cab
2B22cab
2C1cab
3C2cab
3Kb
4C1cab
4C2cab
4C3b
5Cr
PERCENT CaCO3
0
50
PERCENT CLAY
0
50
CLAY/S
0



SOIL PROFILE, EOLIAN DEPOSITS,
DRY WASH, ELK RIDGE AREA
LOCALITY 66

Quaternary Topical Report

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close, but are not contemporaneous at one standard deviation. However, dating of this type of sample is difficult, and the second sample submitted (BETA-6221) was reported as being small for the process (Tamers, 1983).

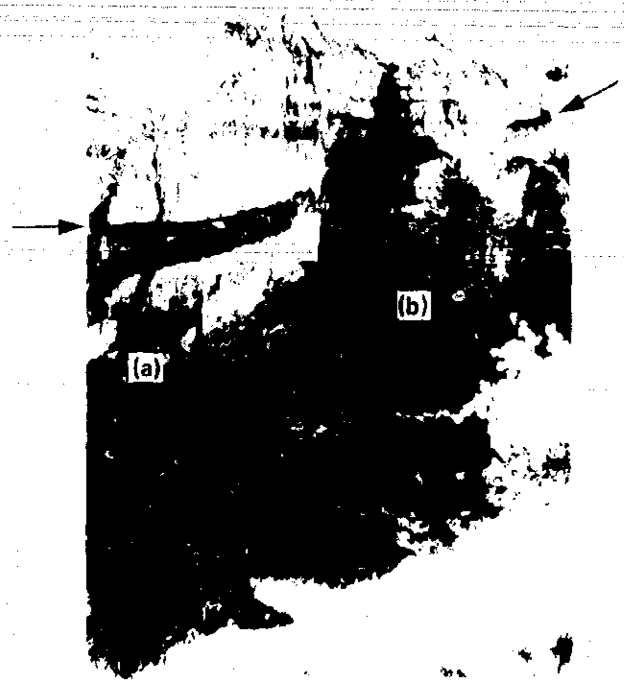
An accuracy assessment of the two ^{14}C dates was made during the amino acid analyses (Section 4.1.4), and by TL dating of associated sediments. When the racemization rates at Locality 67 are compared with those of Locality 63 (where a ^{14}C date of 12,500 years BP was obtained), the younger of the two ^{14}C dates at Locality 67 is considered to be more accurate. However, the error range of the amino acid age estimate at Locality 67 does not exclude either ^{14}C date (McCoy, 1983). A TL sample was collected 0.6 m (2 ft) below the charcoal-rich horizon at Locality 67. The derived TL date of 7,050±640 years is stratigraphically inverted with the radiocarbon date, but is close to the younger ^{14}C date of 7,840±700 years BP.

Another set of ^{14}C and TL dates at Locality 67 was collected from a fill terrace cut into the stratigraphic sequence from which the above dates were derived (Tables 1-1 and 4-9). A radiocarbon date of 2,380±90 years BP was obtained from a burn layer at a depth of 1.2 m (4 ft). The TL sample collected from silty sand 0.1 m (0.3 ft) below the burn layer was dated at 3,690 years ±310 years.

Comparison of the three dating methods in Holocene deposits at Locality 67 resulted in dates that were of the same order of magnitude, but not tightly defined. A 7,000-year TL date for the older fill may be 2,500 years too young, and the duplicate ^{14}C dates vary by 1,500 years. The age range for the amino acid data is also at least this great. The set of ^{14}C and TL dates derived from the fill sequence are stratigraphically consistent. Although the dates at Locality 67 indicate that the three dating methods may not produce identical duplicate dates, they do provide reasonable indicator ages that can be significant when no more precise dating method is available.

4.2.3.1.5 <u>Mule Canyon, Locality 78</u>. An 18-m (60-ft)-thick section of fine-grained deposits is exposed at Locality 78 in Mule Canyon (Figures 1-1, 4-28, and 4-37). Deposits containing a prominent charcoal horizon fill a channel cut into older, more regularly bedded materials. Sediment equivalent to Holocene fill observed elsewhere in the Elk Ridge area underlies a 5.5-m (18-ft)-high terrace that abuts against the older channel fill, adjacent to the stream.

A ^{14}C date was obtained from the charcoal horizon, and amino acid analysis was performed on snail shells collected from above the charcoal, from the base of the channel, and from the older strata cut by the channel (Figure 4-37). The radiocarbon sample (DIC-2063) gave a date of 9,550±80 years BP, the oldest ^{14}C date received thus far on the project from geologic deposits. Interpretation of the amino acid data from the snails collected 15 cm (6 in) above the charcoal gave an approximate age of 11,000 years BP. These snails may have been reworked from the underlying charcoal horizon, and may have been thermally affected by the event that formed the burn layer (Section 4.1.4). Approximate ages of 11,000 years, and 18,000 to 28,000 years BP were calculated for snails collected at the base of the channel fill and from the older strata, respectively.



Holocene and Late Pleistocene fine-grained deposits exposed in 18-m-(60-ft)-high exposure in Mule Canyon, Elk Ridge area. The carbonate-rich deposits that underlie the unconformity in the left half of the photo fill a channel cut into the evenly bedded alluvium seen in the right of the photo. Charcoal collected from the burn layer at the unconformity (arrows) is radiocarbon–dated at 9,550± 80 years BP. Interpretation of amino acid analyses on mollusk shells collected directly above the burn layer and at (a) provide a date of approximately 11,000 years. An age estimate of 18,000 to 28,000 years was similarly derived for mollusk shells collected at (b).

LOG 1740 REV. 0 11/9/83	HOLOCENE AND LATE PLEISTOCENE DEPOSITS, MULE CANYON, LOCALITY 78 Quaternary Topical Report	
	Project No. 17000 **Woodward-Clyde Consultants**	Figure 4–37

4.2.3.1.6 Comb Wash, Locality 79. Mollusk shells were collected from 15-cm (50-ft)-thick gypsiferous deposits preserved in tributary canyons along the western margin of Comb Wash (WCC, 1982a, Vol. III, p. 4-9) (Figure 4-28). The deposits dip 3 to 5 degrees east and may grade to one of the Comb Wash terrace surfaces, which are 12 to 24 m (40 to 80 ft) above the present channel. Because the thermal history of the samples, which were collected approximately 2 m (6 ft) below the surface of the deposits, is uncertain, the age estimated for the amino acid analysis is greater than 9,000 years and less than 30,000 years. No other datable organic material has been found in these deposits.

If the surface of the gypsiferous deposits grades to one of the terrace surfaces that are presently 12 to 24 m (40 to 80 ft) above present stream level, an estimated minimum age for the surface is 50,000 to 100,000 years (using an incision rate of 0.24 m [0.8 ft] per 1,000 years). This age estimate is more consistent with the cemented character of the deposit than the date derived by amino acid analysis. Therefore, the latter is assessed to be too young in this particular geologic setting.

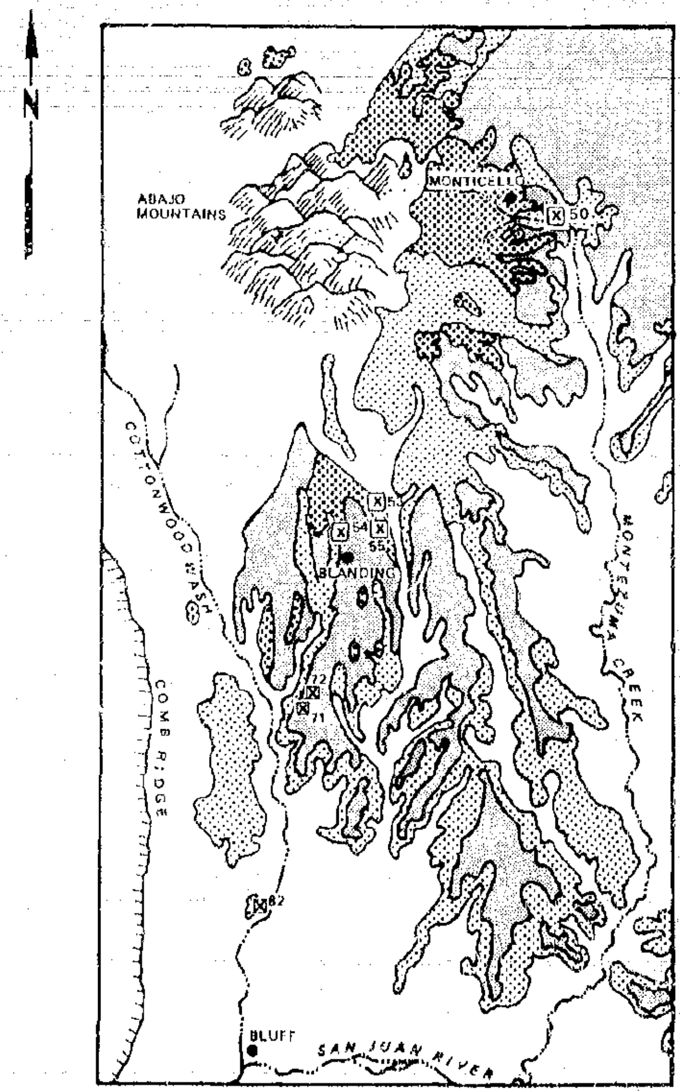
4.2.3.1.7 Summary. At the locations where age dates were derived in the Elk Ridge area, the extent of soil development and induration exhibited by the deposits provided a geologic control against which derived dates were assessed. Where mollusk shells have been found below buried argillic and calcic soil horizons (Localities 65 and 66), amino acid dates of 19,000±4,030 years to 24,000±7,000 years BP for the shells are considered too young. A TL date that provides a maximum age of 44,930±4,030 years BP for the calcic soil at the ER-1 site also seems to be too young, again because of the extent to which calcic soil has developed in the profile.

At Localities 78 and 79, no soil development was noted, so the derived amino acid dates are compared against the local geomorphic setting and induration of the deposits in which they were found. The dates of 18,000 to 28,000 years BP for deposits at Locality 78 are reasonable, whereas the 9,000 to 30,000 dates derived for Locality 79 are assessed as too young.

Samples collected from Holocene deposits (less than 10,000 years old) at Locality 67 provide reasonably comparable dates from radiocarbon, TL, and amino acid analyses.

4.2.3.2 Blanding Area

Quaternary deposits were studied at four locations on a surface(s) thought to be of early Pleistocene age in the vicinity of Blanding (Figure 4-38). Topographic profiling along fan surfaces that flank the southern side of the Abajo Mountains suggests that a pediment surface, capped by fan gravel, merges with the bedrock surface underlain by the Dakota Sandstone/Burro Canyon Formation on White Mesa and other interfluve areas. Abajo terrace gravels found on No Man's Island also lie on the southward projection of the White Mesa surface, as indicated by topographic profiling along Cottonwood Wash (WCC, 1982a, Vol. III, Figure 4-6).



LEGEND:

LOCALITY NUMBER, AS LISTED ON TABLE 1-1

GRAVEL DEPOSITS

FINE-GRAINED DEPOSITS

SURFACE DEVELOPED ON DAKOTA SANDSTONE/ BURRO CANYON FORMATION

0 2 4 6 8 mi

0 2 4 6 8 km

SOURCE: GEOLOGY GENERALIZED FROM HAYNES ET AL., 1972

LOG [illegible]8
REV. 0-9/2/83

GENERALIZED GEOLOGIC MAP SHOWING LOCATIONS OF SOIL PROFILES DESCRIBED IN DEPOSITS OF EARLY PLEISTOCENE AGE NEAR ABAJO MOUNTAINS

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Figure 4-38

4.2.3.2.1 Abajo Mountain Gravel Deposits, Localities 50, 55, and 82. Recently completed carbonate analyses of samples from three soil profiles developed in Abajo Mountain gravels confirm earlier estimates that the deposits are of early Pleistocene age (WCC, 1982a, Vol. III, pp. 4-6 and 4-7). The calcic soils at these sites display several feet of continuous pedogenic carbonate with Stage III to V morphology (Figures 4-39 and 4-40).

Two of the profiles (Localities 50 and 55) are located on the alluvial fans on the southern and eastern flanks of the Abajo Mountains (Figure 4-38). The calcic soil developed on these gravels and exposed in a quarry near Blanding (Locality 55) contains approximately 220 g/cm^2 of pedogenic carbonate in the soil profile (Table 4-5). At the base of this profile and from Localities 53 and 54, which are at comparable elevations, the sandy alluvium has reversed magnetic polarity, indicating a minimum age of 730,000 years. A soil profile formed on gravel deposits near Monticello (Locality 50, Figures 4-39 and 4-40) contains approximately 117 g/cm^2 of pedogenic carbonate in the soil column (Table 4-5). Although no paleomagnetic analyses were made of these deposits, they are thought to be correlative with the Blanding gravel deposits, and are therefore at least 730,000 years old.

Assuming a minimum age of 730,000 years for the Blanding deposit, a maximum long-term carbonate accumulation rate of 0.30 $g/cm^2/1,000$ years is obtained. This rate is higher than the rate of 0.15 to 0.25 $g/cm^2/1,000$ years that was calculated for other areas in the Paradox Basin (Sections 4.1.1.2 and 4.1.1.4.1; Table 4-5). The influx rate at Blanding should be comparable to or lower than that in the Spanish Valley or Green River area because precipitation at Blanding is slightly higher than in the other two areas. Climatic parameters near Monticello would promote even more effective leaching of carbonate from soil profiles (Table 4-3). It is therefore possible that the high carbonate content of the pediment gravels at Blanding indicates that these gravels are older than the Green River or Spanish Valley deposits with reversed polarity. Although almost twice as much soil carbonate was measured in the Blanding soil profile as in the Monticello gravels (Table 4-5), variations in the climatic factors that may affect relative accumulation rates at the two sites, or alternatively, that may affect the rate of carbonate influx, preclude the formulation of relative age assessments.

The third sampled soil profile formed on a terrace remnant with a veneer of gravel derived from the Abajo Mountains. The gravel occurs 140 m (465 ft) above Cottonwood Wash, on No Man's Island (Locality 82; Figures 4-38 through 4-40). The relative elevation of this terrace deposit and reconstructed profiles for Cottonwood Wash terraces (WCC, 1982a, Vol. III, Figure 4-6) indicate that the high terrace deposit is probably correlative with the Abajo Mountain pediments west of Blanding. The soil profile at No Man's Island (Figure 4-40) is developed primarily in eolian deposits that overlie the gravel, and contains approximately 195 g/cm^2 of pedogenic carbonate (Table 4-5). These data confirm that the degree of soil development is similar to that in the pediment gravels and that the deposits are probably of comparable age. An estimated age of 770,000 to 1,285,000 years is derived for these deposits, using a pedogenic $CaCO_3$ accumulation rate of 0.15 to 0.25 $g/cm^2/1,000$ years.

Calcic soil development in Abajo fan gravel exposed in gravel pit at Monticello (Locality 50). Calcic soil is truncated and overlain by younger eolian deposits.

Petrocalcic soil development on fine-grained deposits overlying gravel terrace deposits on No Man's Island (Locality 82).

CALCIC SOIL DEVELOPMENT ON ABAJO MOUNTAIN DEPOSITS

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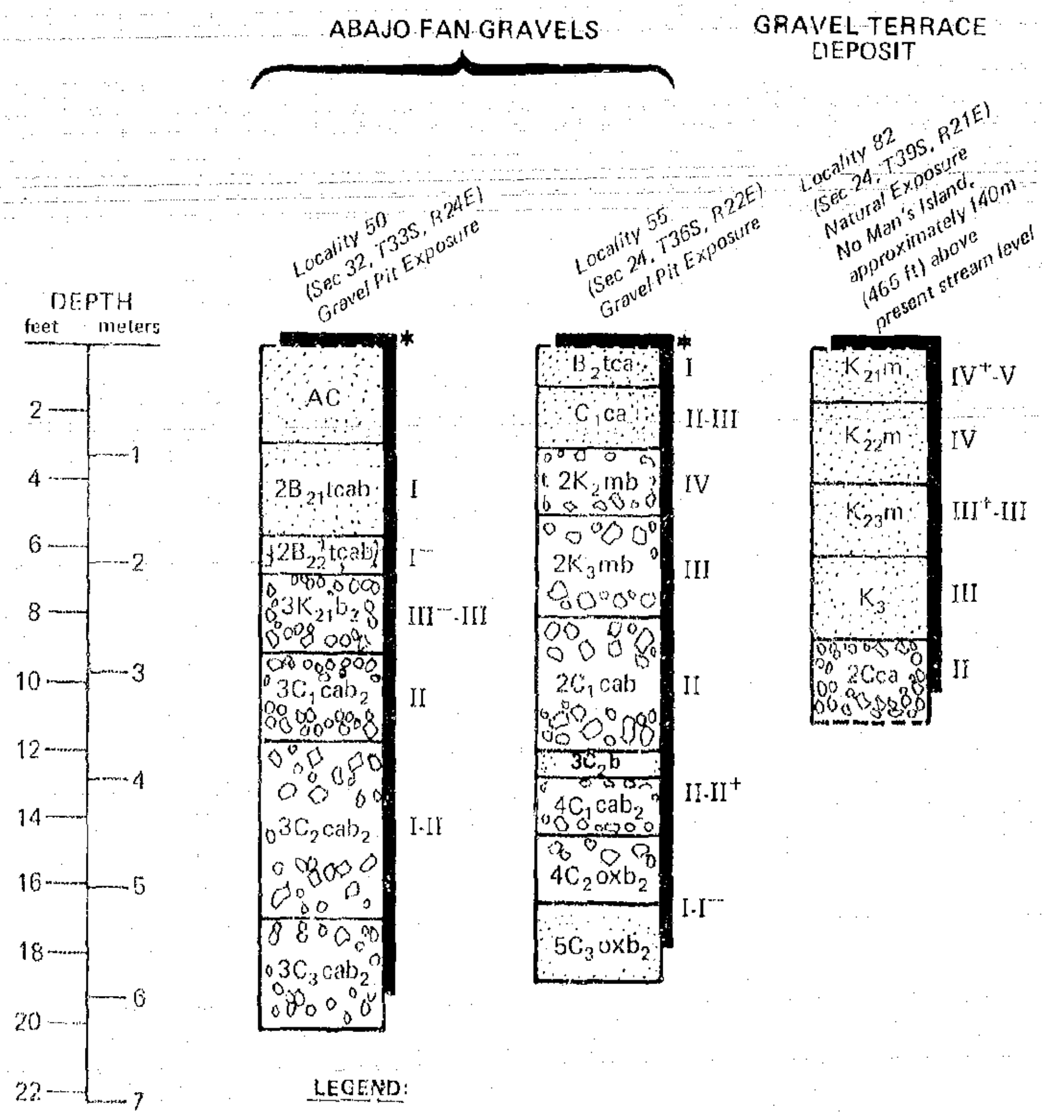
Figure 4–39



LEGEND:

* UPPER PART OF PROFILE REMOVED BY GRAVEL PIT OPERATION

C_3cab FIELD CLASSIFICATION OF SOIL HORIZON (FIGURE 4-1)

ARGILLIC B HORIZON

GRAVELLY PARENT MATERIAL

SANDY PARENT MATERIAL

II STAGE OF CARBONATE MORPHOLOGY (TABLE 4-2)

NOTE: LOCATIONS OF SOIL PROFILES ARE SHOWN ON FIGURE 1-1, 4-38

LOG 1594
REV. 2-8/29/83

SOIL PROFILES ON GRAVEL DEPOSITS FROM ABAJO MOUNTAINS

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Figure 4-40

4.2.3.2.2 White Mesa, Localities 71 and 72. Laboratory data were derived from two soil profiles developed in eolian deposits at the southwestern end of White Mesa (Localities 71 and 72), approximately 11 km (7 mi) south-southwest of Blanding (Figure 4-38). White Mesa is a southward-dipping surface cut on the Cretaceous Burro Canyon Formation and Dakota Sandstone (Haynes et al., 1972), and has been interpreted to be correlative with the pediment surface north of Blanding, which is underlain by Abajo gravels with reversed magnetic polarity. Therefore, the White Mesa surface is probably at least 730,000 years old.

The two soil profiles have formed in 2.2 to 2.9 m (7 to 9.5 ft) of sandy loam, which consists primarily of well-sorted very fine and fine sand (Figures 4-41 through 4-43). The deposits are massive and appear to be predominantly of eolian origin. The eolian material may be derived from local sources, particularly dry stream beds, as postulated by Olsen et al. (1945, p. 38), or it may have been blown in from more distant exposed sandstone bedrock areas to the southwest. A few highly weathered cobbles and pebbles derived from the Abajo Mountains were observed in the lower part of Profile 1; deposits in this profile may therefore be partly alluvial. At both sites, the fine-grained deposits overlie weathered sandstone bedrock.

The degree of calcic soil development is markedly different in the two sampled profiles (Table 4-24). At Profile 1 (Locality 72; Figure 4-38), exposed in a bulldozer trench excavated by Energy Fuels Nuclear, Inc., at least two well-developed calcic soils are present (Figure 4-41 and 4-42). A third buried calcic soil is probably represented by the $CaCO_3$-rich horizon formed on bedrock at the base of the profile. A buried argillic horizon has apparently been partly engulfed by the middle K horizon. In contrast, Profile 2 (Figure 4-43), exposed in a backhoe excavation (Locality 71), shows little calcic soil development; only weak increases in $CaCO_3$ content are seen in the profile (Figure 4-43). However, a buried argillic horizon, which may be correlative with that seen in Profile 1, is preserved in Profile 2.

The difference in calcic development in the two profiles is probably a result of the topographic position of the two sites. Profile 2 is located at the head of a small swale that drains into Cottonwood Wash; carbonate may not be retained in this profile because of increased leaching. Profile 1 is located on a topographically higher area, where through-flowing drainage would be minimal. The presence of buried argillic horizons, which are inferred to be correlative, supports this hypothesis.

Alternatively, the buried eolian deposits in Profile 2 may be considerably younger than the buried deposits in Profile 1. The TL dates for t deposits at these sites are supportive of this second theory. A TL sample collected at the base of Profile 2 has a date of 32,700±2,850 years, whereas the samples in Profile 1 produced TL dates ranging from 46,700±3,950 to 137,000±10,900 years (Table 4-23). The TL date of 137,000±10,900 years was derived for the calcrete formed on the Cretaceous sandstone bedrock in Profile 1. It is much older than the basal TL date for Profile 2, but it is anomalously young when compared with the soil carbonate data.

If the basal TL sample represents Quaternary sediments present on top of the bedrock, and if the TL date is correct, the carbonate at the base of the soil profile (Figure 4-42) must be partially nonpedogenic. Published

Multiple calcic soil horizons (arrows) developed in eolian deposits on White Mesa. Exposure is at Locality 72 on Figure 4–38.

CALCIC SOILS IN EOLIAN DEPOSITS ON WHITE MESA, NEAR BLANDING

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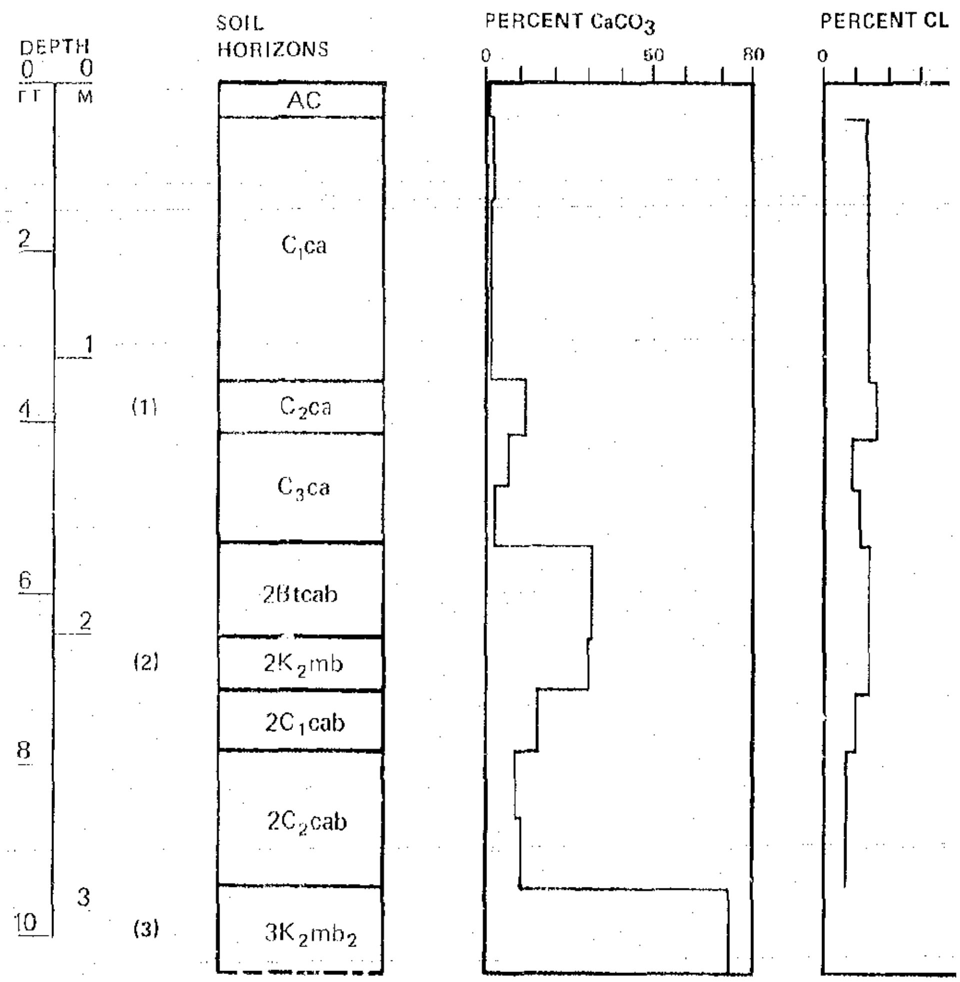
Figure 4–41

Table 4-24. Accumulation of Calcium Carbonate in Soils Formed in Quaternary Eolian Deposits on White Mesa

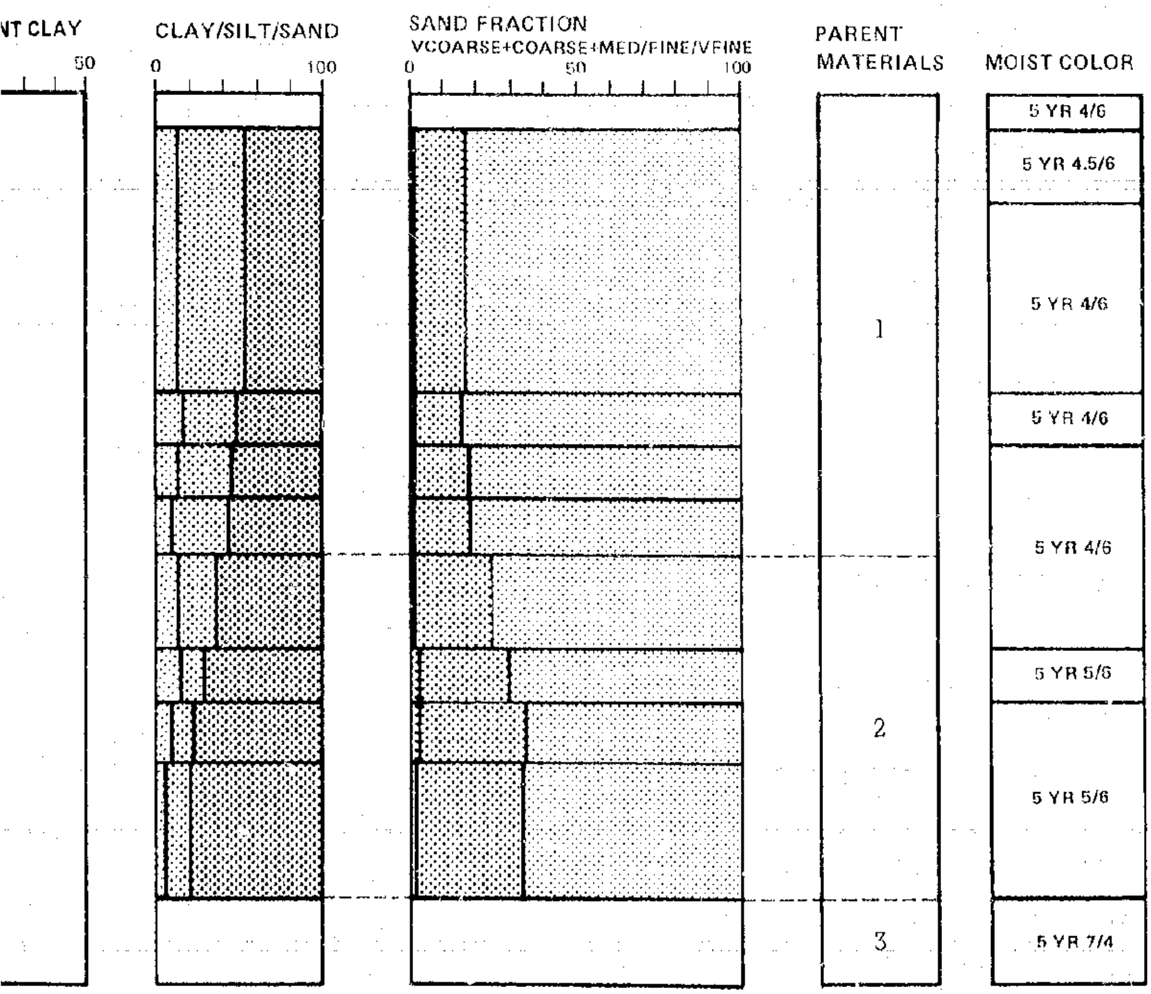
Locality	Site	Portion of Profile	No. of Samples Analyzed	Total $CaCO_3$ Content (gm/cm^2)	Estimated $CaCO_3$ Content of Original Parent Material (%)	Estimated $CaCO_3$ Content of Original Parent Material (g/cm^2)	Estimated Pedogenic $CaCO_3$ (g/cm^2)
71	Sec.32, T37S, R22E-1 (backhoe pit)	Total	11	15.3	0.3	1.1	14.2
		Soil horizons overlying 2Ccab horizon developed on bedrock	10	8.3	0.3	1.0	7.3
72	Sec.33, T37S, R22E-1 (bull-dozer trench)	Total	13	97.7	1.0, 3.5[a]	14.1	83.6
		Soil horizons overlying 3K2mb2 horizon developed on bedrock	12	60.6	1.0, 3.5[a]	12.4	48.2

(a) Parent material for lower soil appears to be more calcareous than upper parent material.



THERMOLUMINESCENCE DATES:

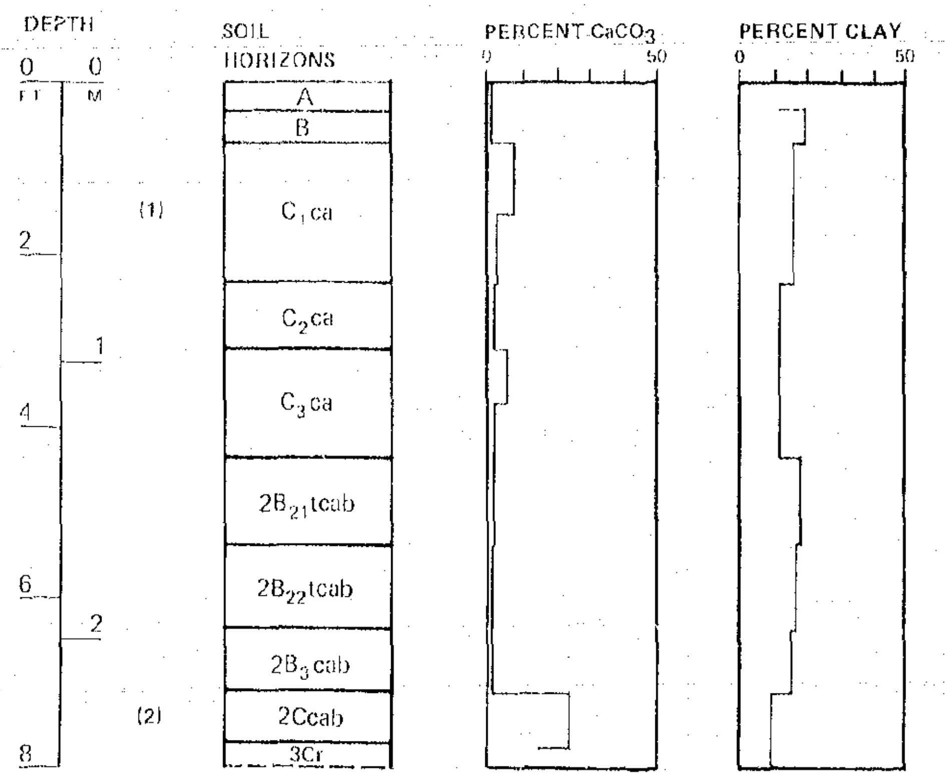
(1) 46,700 ± 3,950 years BP
(2) 93,800 ± 7,000 years BP
(3) 137,000 ± 10,900 years BP



WHITE MESA, SOIL PROFILE 1
BULLDOZER TRENCH
LOCALITY 72

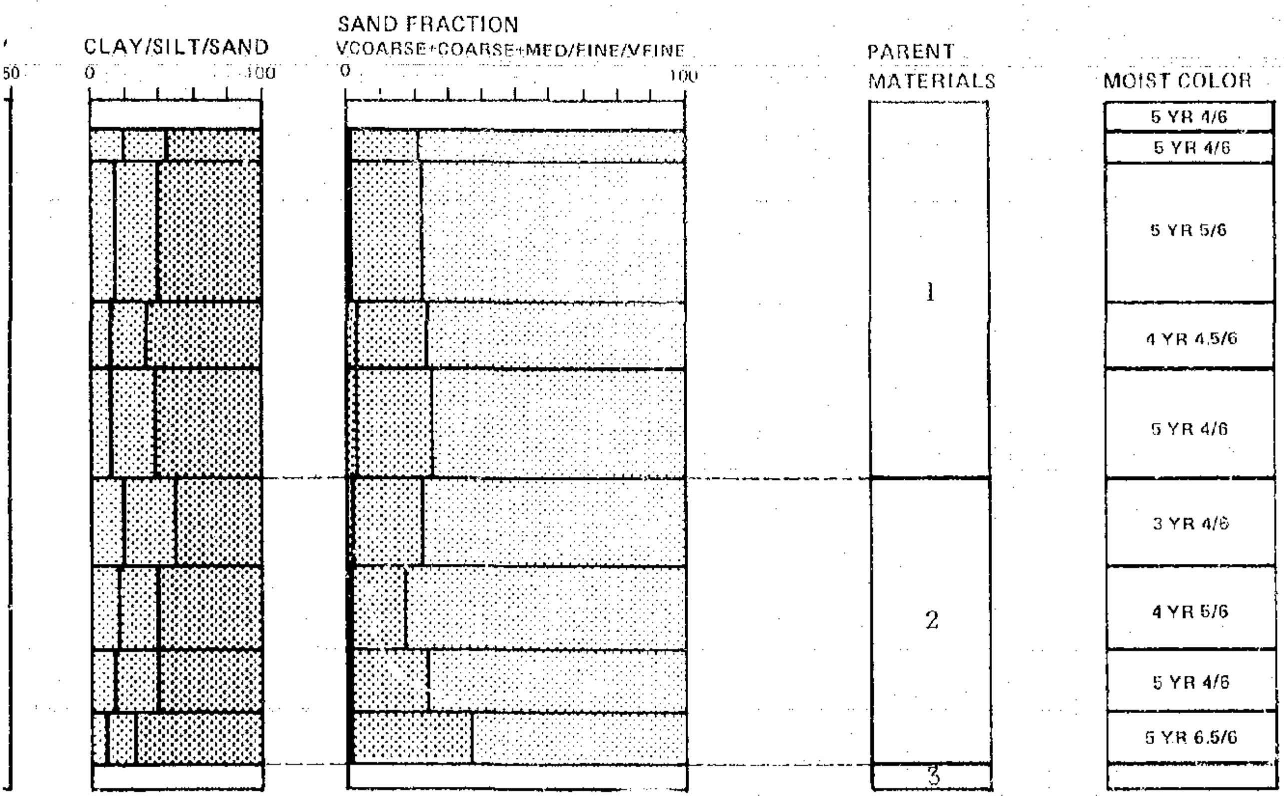
Quaternary Topical Report

Project No. 17000 Woodward-Clyde Consultants	Figure 4-42



THERMOLUMINESCENCE DATES:

(1) 24,000 ± 2,300 Years BP
(2) 32,700 ± 2,850 years BP



WHITE MESA, SOIL PROFILE 2:
BACKHOE PIT,
LOCALITY 71

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Figure 4-43

(Tables 4-4 and 4-5). Using long-term carbonate accumulation rates carbonate contents for the Burro Canyon and Dakota sandstones, however, are less than approximately 10 percent (Craig, 1981; Huff and Lesure, 1965); therefore, much of the carbonate is probably pedogenic. Thus, it seems likely that the TL date at the base of Profile 1 is anomalously young, and that basal deposits observed in the bulldozer trench are older than those exposed in the backhoe pit.

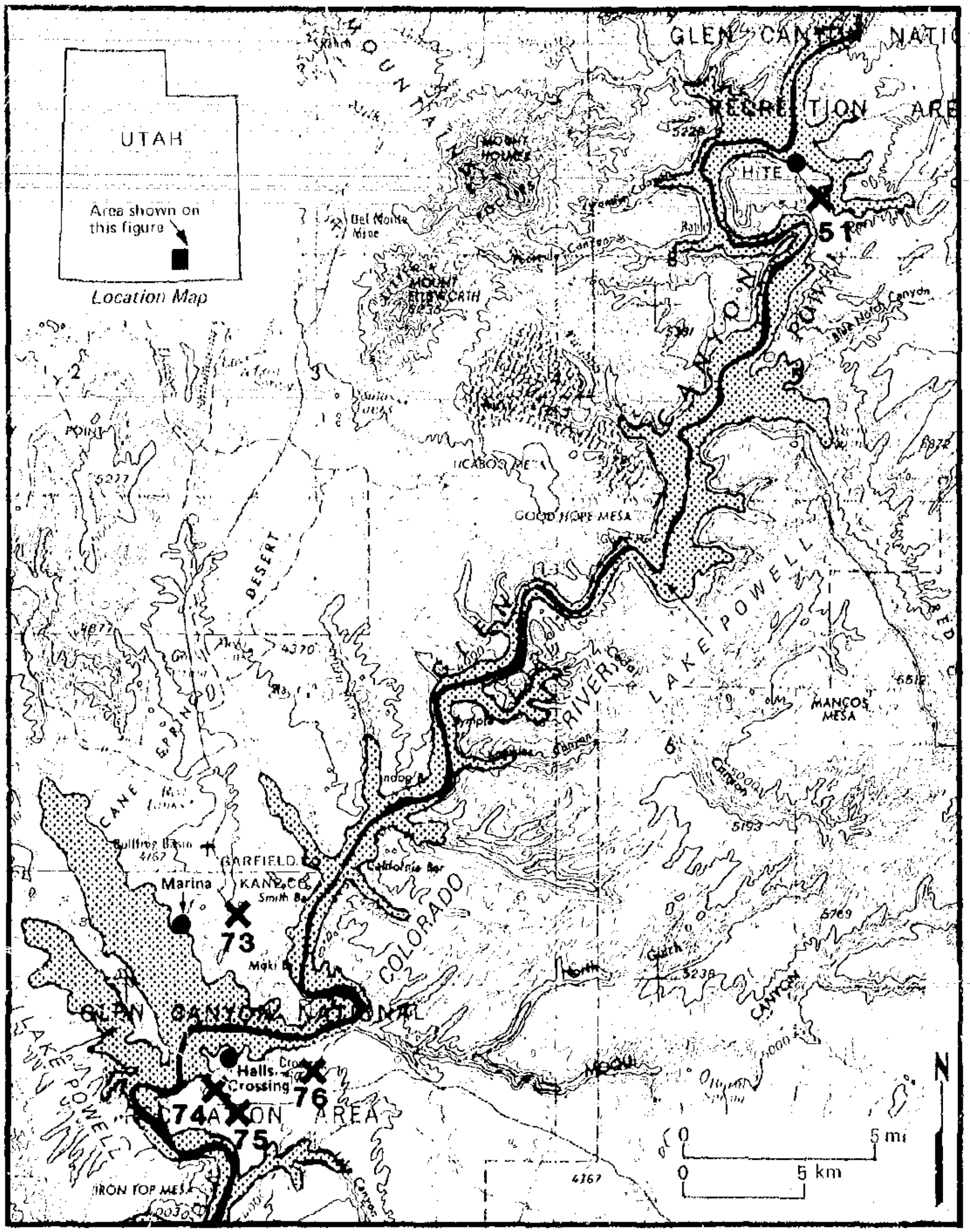
Based on the pedogenic carbonate content of Profile 1 (Locality 72), it appears that the White Mesa surface is of mid-Pleistocene age or older. A total of 84 g/cm^2 of pedogenic carbonate is present in this profile established for other portions of the Paradox Basin (Section 4.1.1.4.1), the age estimated for the eolian deposits on the surface is between 335,000 and 560,000 years. Alternatively, if it is assumed that the White Mesa deposits are correlative with the early Pleistocene surface at Blanding (>730,000 years), the estimated maximum carbonate accumulation rate for the White Mesa area would be 0.12 g/cm^2/1,000 years. This rate is less than the rate of 0.30 g/cm^2/1,000 years derived for the Blanding gravels, and is more comparable to the Fisher Valley rate of 0.15 g/cm^2/1,000 years. Therefore, although the White Mesa surface may be correlative with the Blanding pediment surface, the eolian deposits described in the soil profiles appear to be younger than the Blanding gravels. Deposits that are correlative with the Blanding gravels may be preserved locally elsewhere on White Mesa, or they may have been completely eroded from the surface.

4.2.3.3 Colorado River

Fluvial and eolian deposits of probable early Pleistocene age underlie surfaces between 200 and 250 m (600 and 800 ft) above the Colorado River (Figure 4-44). These terrace deposits are particularly abundant in the vicinity of Hite (Locality 51) and Bullfrog Basin (Localities 73, 74, and 76; Figures 1-1 and 4-44), west of the Elk Ridge area.

4.2.3.3.1 <u>Hite, Locality 51</u>. Thaden et al. (1964) described a 10-m (33-ft)-thick section of fine-grain sediments overlain by approximately 8 m (25 ft) of fan debris in an abandoned meander of the Colorado River at Hite (Locality 51). These authors speculated that source sediments collected in the abandoned channel after landslides blocked the downstream end of the meander. The surface of the old river channel, observed beneath the badland topography of the fine-grained deposits, can be seen along the shore of Lake Powell and is approximately 90 m (300 ft) above the bottom of the canyon. Using the long-term regional incision rate of 0.24 m (0.8 ft) per 1,000 years (WCC, 1982a, Vol. I, p. 3-20), the abandoned meander was probably isolated from the main river channel approximately 375,000 years ago. Mollusk shells found in the lowest section of the fine-grained deposits would therefore be younger than the isolated meander by an unknown amount.

The amino acid ratios derived from the mollusk shells sampled at Locality 51 indicate that they are much older than any of the other shell samples analyzed (Tables 4-11 and 4-12). The alle/Ile ratio for the <u>Physa</u> shells is comparable to that of <u>Lymnaea</u> shells found below the Lava Creek ash (610,000 years BP) in Little Valley, Utah (Lake Bonneville) (Table 4-12).



LEGEND:

73 LOCALITY NUMBER, AS LISTED ON TABLE 1–1

LAKE POWELL

LOG 2329 REV.0–9/19/85	LOCATION OF SAMPLE LOCALITIES ALONG THE COLORADO RIVER Quaternary Topical Report	
	Project No.17000 Woodward-Clyde Consultants	Figure 4–44

Locality 51 has a higher effective temperature than Little Valley, and Physa shells have a higher rate of isoleucine epimerization than Lymnaea shells; on this basis, the age of the Locality 51 sample was estimated to be 500,000 (+300,000, -200,000) years. The large uncertainty reflects the uncertain thermal history of the sample, the uncertainty in the isoleucine epimerization rate in Physa shells, and the large analytical error noted in duplicate runs of the sample. Some of the analytical error may be the result of contamination, as suggested by comparing other amino acid contents of the sample. The bulk of the data indicates that the sample is more rather than less than 500,000 years old (McCoy, 1983).

The age estimate derived from amino acid analyses at Locality 51 is older than the estimate based on assumed long-term rates of incision. At this location, the amino acid data may more accurately reflect the age of the deposits because the incision rate that has been used is considered to be conservatively high (WCC, 1982a, Vol. I). Data derived from the history of Colorado River development indicate that the river probably started forming the present canyon system much earlier than is indicated by an incision rate of 0.24 m (0.8 ft) per 1,000 years, and that the rate may more accurately be 0.12 m (0.4 ft) per 1,000 years, or less.

The deposits at Hite provide an excellent opportunity to assess the accuracy of the assumed incision rate and the ages estimated from amino acid analyses because the sediments are sufficiently fine-grained for paleomagnetic analysis. If they were found to be paleomagnetically reversed, the incision rate in the last 730,000 years would have averaged 0.12 m (0.4 ft) per 1,000 years, or less.

4.2.3.3.2 Halls Crossing, Localities 73, 74, and 76. Age assessment of these deposits was based on the visual evaluation of the degree of pedogenic carbonate accumulation in the deposits, their topographic position and paleomagnetic signature, and TL analysis. The highest terraces have a Stage IV to V calcic soil; a gravel and sand terrace at Bullfrog Basin (Locality 73), at an elevation of 195 m (635 ft) above the canyon bottom, is paleomagnetically reversed. These data indicate probable ages between 730,000 and 2.3 million years for the high deposits. TL dates for the same deposits are anomalously young (Section 4.1.3.4; Table 4-8); dates obtained from two sites (Localities 74 and 76) range from 140,000±11,800 to 307,000±39,300 years BP (Tables 1-1, 4-8, and 4-19).

4.3 EVALUATION OF AGE DATING METHODS

Several age dating techniques applied to the Quaternary deposits of the Paradox Basin provide estimates of the rate at which geomorphic processes are occurring in the area. Where conditions and materials permitted, multiple methods were applied to individual sites to compare the results and to assess the accuracy and reproducibility of the various methods used. This section summarizes the strengths and limitations of the various methods, and their applicability to the geologic setting of southeastern Utah.

4.3.1 Pedogenesis

The characteristics of pedogenic horizons developed in Quaternary deposits provide a means of assessing their relative ages. The accumulation of $CaCO_3$ in soil profiles has been useful in identifying sequences of buried deposits in the Paradox Basin Quaternary studies, and in estimating their relative and approximate ages. The method provides an age approximation for a deposit rather than a well-defined date. The estimated accuracy of the technique is ±30 to 50 percent. Summary statements about this correlation method, including derived conclusions and recommendations, are given below (Sections 4.3.1.1 and 4.3.1.2).

4.3.1.1 Conclusions

1. In the Paradox Basin studies, accumulation of soil carbonate provided visual, qualitative means of comparing relative ages of deposits; and quantitative assessments of the ages of deposits through the calculation of the amount of pedogenic carbonate in the soil profile. This relative dating method was found to be applicable throughout the Paradox Basin, except at elevations above the base of the local mountains.

2. Age assessments based on calcic soil development were acceptably comparable to a previously established glacial chronology in the Spanish Valley correlation area, south of Moab. In the Paradox Basin study region they also exhibit a direct correlation with the height of the deposit above present stream level, and were comparable to TL dates derived from the same localities.

3. Age assessments determined from pedogenic carbonate accumulations utilize a regional long-term carbonate accumulation rate, and assume that soil carbonate accumulation is a linear function of time. The range of maximum accumulation rates calculated for the Paradox Basin by utilizing deposits with reversed paleomagnetic polarity is 0.15 to 0.30 $g/cm^2/1,000$ years. Relatively accurate dates were used by the USGS to calculate a rate of 0.15 $g/cm^2/1,000$ years for a thick sequence of Quaternary deposits in Fisher Valley, 29 km (18 mi) east of Moab (Colman, 1983). This rate represents the most precisely determined long-term carbonate accumulation rate available in the area. Because of the variability in the influx rate over such a broad area and time is unknown, and because erosion may have removed some of the age-bracketed sequence, ages calculated in this report use an accumulation rate of 0.15 to 0.25 $g/cm^2/1,000$ years. The carbonate influx rates developed during the Paradox Basin studies are maximum rates because a minimum age of 730,000 years has been assumed for the deposits with reversed paleomagnetic stratigraphy.

4. Short-term influx rates (i.e., for the Holocene) may be several times higher than the long-term rates. This may be due to local or regional influences.

5. Part of the pedogenic carbonate accumulated in a soil profile may be (1) removed by erosion, or (2) leached from the profile if the climate or ground-water flow changes sufficiently. Local variations in soil carbonate accumulation may be significant because of nearby structural, topographic, or erosional control. Alternatively, it may be difficult to ascertain the amount of carbonate that has been derived from carbonate cement in the underlying bedrock or from clasts in a gravel deposit, or to assess if the accumulation of soil carbonate was limited by either excessive or insufficient rainfall over significant periods of time.

6. Stream-deposited carbonate can accumulate in deposits in close proximity to intermittent streams. It is difficult to differentiate between pedogenic and ground-water- or stream-deposited carbonate, either in the field or in laboratory analyses of the deposits.

7. Reproducibility of the laboratory soil data used to calculate long-term carbonate influx rates was good. Also, measurements could be reproduced within 5 percent on 80 percent of the disguised duplicate samples that were submitted for calcimeter analysis. Therefore, the greatest potential sources of error in age assessments based on this technique are in the assumptions made about (1) the $CaCO_3$ content of the parent material; (2) a constant rate of retention of airborne carbonate in the soil profile; (3) carbonate that may be deposited by ground water; and (4) application of a uniform, long-term accumulation rate that may in actuality be subject to local and temporal variations.

4.3.1.2 Recommendations

1. Pedogenic carbonate assessments should continue to be used in Paradox Basin studies to provide a useful qualitative and quantitative means of correlating Quaternary deposits.

2. Means should be developed to address the local carbonate influx for the area of interest, and the variation in the influx rate through time. Such background data could provide an assessment of the accuracy of the quantitative age estimate.

4.3.2 Carbon-14

Materials suitable for radiocarbon dating were found in the Paradox Basin, and dates as old as 10,000 years BP were obtained from collected samples. This method proved to be one of the primary means of dating fine-grained Holocene deposits. A summary of findings and experience of using the ^{14}C dating techniques in Paradox Basin Quaternary deposits includes conclusions and recommendations listed in Sections 4.3.2.1 and 4.3.2.2, respectively.

4.3.2.1 Conclusions

1. Although materials suitable for radiocarbon dating are present in Paradox Basin deposits, they are very sparse and tend to be less than 10,000 years BP in age. No dates older than this were derived in the Paradox Basin studies.

2. Many samples collected in the field and thought to be representative of the deposit of interest provided age dates that were assessed to be too young. It was concluded that these samples were probably sections of burnt root that substantially postdated the age of the deposit, but were difficult to recognize in the field.

3. Mats of vegetation debris deposited in flood events are most likely to provide a date that accurately reflects the age of a deposit in the depositional environment of the Southwest. These represent a short instance in geologic time, and are not apt to contain material reworked from older depositional units.

4. Use of a method that can accept small samples (as little as 30 mg in weight) resulted in dates that were as accurate as results derived by other radiocarbon laboratory methods. However, with such small samples, the amount of material available was insufficient to permit verification of dates through duplicate dating of split samples.

5. Stratigraphically inconsistent dates may have been due to the small size of a sample, the contamination of a sample by soil solution, or the incorporation into the deposit of charred wood significantly older than the deposit.

6. In evaluating the reproducibility of radiocarbon data by submitting blind duplicate samples to laboratories, only two of eight duplicate samples exhibited contemporaneity. This exercise demonstrated the need to have samples of adequate size for duplicate analysis, and to thoroughly homogenize a sample before it is split into two or more portions.

7. At the present time, derived "good" ^{14}C dates are not sufficient to differentiate chronologically those separate Holocene units that appear correlative. It is not clear whether this is because the samples are too small; because the age of the charcoal does not reflect the age of the deposit in which it was found; or because the deposits are time-transgressive, and therefore may show no chronologic synchroneity.

4.3.2.2 Recommendations

1. More than one sample per site should be submitted for analysis to evaluate the test results for stratigraphic reasonableness.

2. The collection of chunks or pieces of charcoal that occur randomly in fine-grained deposits should be avoided. These could represent charcoal reworked from an older deposit, or a recently deceased tree that is significantly older than the deposit. They will provide only a maximum age for the sampled horizon.

3. In submitting duplicate samples to test the reproducibility of laboratory results, the whole sample should be thoroughly ground and mixed before splitting for the separate analyses.

4.3.3 Thermoluminescence Dating

A total of 57 TL dates was derived from a variety of sedimentary deposits in the Paradox Basin. Conclusions, and recommendations for subsequent TL dating analyses, are summarized in the following sections (Sections 4.3.3.1 and 4.3.3.2).

4.3.3.1 Conclusions

1. Based on the evaluation of the TL dates obtained in the Paradox Basin Project, the TL dating technique is assessed to be potentially very useful as an age-dating tool for Quaternary studies in the Southwest.

2. Almost all of the derived TL dates, except for those from deposits estimated to be older than 300,000 years, are stratigraphically consistent, and are of the same order of magnitude as ages estimated from pedogenic carbonate content in soil profiles. Correlation between TL dates and pedogenic carbonate data is favorable for sites having a pedogenic carbonate age of <200,000 years BP.

3. TL-derived dates from deposits interpreted on the basis of topographic position or calcic soil morphology to be more than 300,000 years in age were assessed to be too young. One explanation for this observation is that young eolian material filters downward through the soil profile and "contaminates" the older underlying deposits, resulting in a date that is an average of the ages of the two parent materials.

4. An alternative explanation for the inability of the TL method to provide dates older than approximately 300,000 years for early Pleistocene deposits is that samples are saturated with the amount of thermoluminescence that can be contained in the crystal lattices of minerals. This would create an upper limitation on the applicable TL dating range.

5. Ten TL samples were collected from six sites where sufficient radiocarbon material was available for dating. The results of the TL analyses are in general agreement with ^{14}C dates at two sites, but the ranges of the two sets of dates do not overlap. Results from two other carbon-dated sites are stratigraphically

acceptable, whereas the dates from the fifth and sixth sites are anomalous (Table 4-9). The old (59,100±6,780 years) TL age for a Holocene deposit at one of these sites suggests that the dated fluvial deposit did not completely lose its previous TL signal prior to burial.

4.3.3.2 Recommendations

1. Continued application of the TL dating technique to Quaternary studies is recommended, particularly in areas such as the Southwest, where fine-grained (particularly eolian) deposits are common.

2. Although silt-size particles separated from gravel samples provided geologically reasonable dates in the Paradox Basin studies, the collection of gravel for age assessments by this technique is not recommended. The inhomogeneities in the gravel clasts can introduce too many variables that cannot be assessed and removed in the TL laboratory analyses.

3. The TL dating method is still considered by many to be an experimental technique because it has not been widely applied or tested. Therefore, duplication or verification of derived dates is recommended to ensure the accuracy of the data.

4.3.4 Amino Acid Diagenesis

Ages were estimated for 13 samples of mollusk shells and 12 soil samples on the basis of amino acid ratios in the samples. Conclusions and recommendations in the following sections (Sections 4.3.4.1 and 4.3.4.2) summarize the application of this dating method to Paradox Basin studies.

4.3.4.1 Conclusions

1. Some of the age estimates derived from the amino acid analyses are in accordance with the age interpreted for the deposits by other means. Other derived ages were assessed to be too young.

2. The derived age estimates are expressed in a broad range (±15 percent), reflecting the uncertainty in estimating the paleothermal history, which is determined by depth burial and paleoclimatic conditions.

3. An amino acid analysis in conjunction with ^{14}C dates or other age control, can be used to develop paleoclimatic assessments for an area because the amino acids are temperature sensitive.

4. The analyzed soil samples were collected from nine carbonate-rich and three clay-rich horizons. The allo/ile (?) ratio for the calcic soils demonstrated no correlation with the expected age of the material, indicating that the samples contain recently

infiltrated organic matter or that carbonate has continued to accumulate in the upper part of the soil. Data from the argillic soil horizons appear to have more direct correlation with sample age. The data base is limited, however, and more study is needed to thoroughly evaluate the feasibility of dating soils using amino acid analysis. Without additional research, the method did not demonstrate sufficient promise for further application to this project.

4.3.4.2 Recommendations

1. Sampling of mollusk shells for amino aci[illegible] estimates should continue in order to improve the assessme[illegible] the accuracy of this method. Although some of the derived dates from mollusks were assessed to be too young in the Paradox Basin studies, this evaluation may be in error. At the present time, there is not adequate age control for deposits in which the shells were found, and the assessment is based on the extent of calcic soil development in the overlying horizons.

2. Further collection of soil samples for amino acid analyses is not recommended for future Paradox Basin Quaternary studies, given the present understanding of the method. If additional research refines its application as a correlation or dating technique, reconsideration of this recommendation may be warranted.

4.3.5 Paleomagnetism

The paleomagnetic signature of sediments has been used most extensively on this project to identify deposits that are at least 730,000 years old (i.e., that are paleomagnetically reversed). Knowing the minimum age of Quaternary strata of interest provides a maximum rate for geomorphic or geologic processes that have affected that deposit at the locations where data are available.

4.3.5.1 Conclusions

1. Sediments that are at least 730,000 years old were identified at seven localities during the study, and long-term incision rates and carbonate influx rates were calculated on the basis of these data.

2. Many of these samples display evidence of a complex history of magnetization. Some of this complexity appears to be associated with the case-hardening effect that typifies the surfaces of natural exposures; the paleomagnetic signature was less complex for samples that had been collected at least 0.3 m (1 ft) from the face of the outcrop.

3. Paleomagnetic analyses of Holocene deposits indicated that a consistent trend in a secular variation pattern could be detected

for strata that were radiocarbon-dated between approximately 720±550 and 1,600±100 years BP. However, in order to construct a secular variation curve for the last 5,000 to 10,000 years, and to apply it to the correlation of Holocene sediments in the Paradox Basin, additional sampling and radiocarbon analyses are needed. This particular application of paleomagnetic analysis has not been further pursued.

4.3.5.2 Recommendations

1. Paleomagnetic signatures should continue to be used to identify deposits of early Pleistocene age (>730,000 years) in the Paradox Basin. Of particular interest is the bracketing of the Bruhnes-Matuyama reversal in terrace deposits along the Colorado River in order to establish an incision rate that is definitive for the area.

2. Additional use of remanent magnetization as a means of correlating Holocene deposits in the Paradox Basin is not recommended. More effective dating techniques are available.

4.3.6 Uranium-Series Analysis

Use of U-series analysis to date a limited number of carbonate rinds appears to provide dates that are too young; however, a U-series date on a mammoth(?) tusk is thought to be too old. An insufficient number of samples was run during the project to adequately evaluate the U-series dating method. Reproducibility of the data should be further assessed by dating sample suites (3 or 4 samples each) collected from the same soil horizon at one locality.

4.3.7 Relative Weathering

Relative weathering methods that were assessed for their usefulness in distinguishing Quaternary deposits of varying ages are (1) weathering-rind thickness on igneous cobbles in gravel terraces; (2) etching of heavy mineral grains in specific soil horizons; and (3) X-ray analysis of clay, quartz, and feldspar minerals in soil profiles.

Measurement of weathering rinds at the Spanish Valley correlation area and at the Indian Creek terrace site in the Gibson Dome area revealed no sufficiently definitive trend of rind thickness with increasing age of the terrace. This general lack of correlation has been attributed to variability in lithology of the clasts, spalling from the outer surface of the clasts, and deceleration of weathering caused by carbonate accumulation on the clasts.

The extent of etching of hornblende and augite mineral grains was compared with ages of deposits at four locations in the Paradox Basin. The trends observed were too poor to consider using the technique in subsequent studies. Etching appears to be proceeding slowly, possibly because of the low rainfall amounts in the areas examined. Other complicating factors included recycling of etched grains, potentially different weathering histories for buried and relict soils on parent materials of similar age, and the lack of augite in Quaternary gravel derived from the Abajo Mountains.

The use of X-ray analysis of silt- and clay-size material collected from a soil profile shows promise as a relative dating method and a means of correlating Quaternary deposits. Although a weathering index that compares quartz and feldspar peak intensities does not show any consistent trend within soil profiles, the characteristics of X-ray diffractograms appear useful in defining depositional contacts and soil horizons within a sampled exposure. These interpretations can be compared with variations in intensity values for quartz, feldspar, and clay peaks on the diffractograms, which also collectively define breaks in the depositional and/or pedologic process. The overall trend is that intensity values of the quartz and plagioclase minerals decrease with age; however, because of the lack of data, it has not yet been possible to assess the correlative possibilities of the method.

4.3.8 Topographic Position

Use of topographic position, (i.e., the elevation of a deposit or surface above present stream level) to derive an age assessment is applicable to the Paradox Basin area, where relief is high and stream incision has been in progress for hundreds of thousands of years. A (maximum) long-term incision rate of 0.24 m (0.8 ft) per 1,000 years for the major rivers (the Colorado, San Juan, and Green Rivers) in the Paradox Basin region can be used to estimate the approximate (minimum) age of deposits whose height above present stream level is known. Although the incision rate is assumed to be constant in these calculations, it probably varies in response to climatic changes and lithologic variations encountered in the downcutting process. The method is not applicable to Holocene fine-grained deposits, because stream incision has apparently been minor during Holocene time. Fine-grained material has probably been repeatedly flushed from and deposited in bedrock channels throughout the area during Holocene time.

Topographic position may not be useful as an age indicator where a deposit or surface has been topographically disrupted by faulting or by salt dissolution and subsidence. However, the anomalous topographic setting in these situations can provide an indication of the amount and perhaps the rate at which deformation is occurring.

4.3.9 Summary

On the basis of the data gathered for this project, the techniques that were assessed as most applicable to current studies are the accumulation of pedogenic carbonate in soil profiles, radiocarbon dating, TL dating, amino acid diagenesis, paleomagnetic analysis of early Pleistocene deposits, and topographic position of deposits and surfaces. Application of these techniques to future Quaternary studies should continue during site characterization studies. If surficial deposits are present, these methods can also be used to evaluate the activity of faults or rate of salt dissolution during Quaternary time.

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